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ff 653 July 65

FACILITY FORM 602

N67-17120 (ACCESSION NUMBER)	(THRU)
156 (PAGES)	1 (CODE)
CR-81523 (NASA CR OR TMX OR AD NUMBER)	03 (CATEGORY)

JET PROPULSION LABORATORY

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PASADENA, CALIFORNIA

TR 34-66-31 (U)

A STUDY OF THE CONCEPTUAL DESIGN OF A REMOTE CONTROL STATION

Final Report

September 1966

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Prepared for:

CALIFORNIA INSTITUTE OF TECHNOLOGY
Jet Propulsion Laboratory
Contract No. 951313

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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ABSTRACT

This report presents the results of a study program to: (1) develop a method to determine and evaluate future requirements for operators in the real time command/control loop during unmanned spaceflight operations from the facilities of the Jet Propulsion Laboratory, and (2) derive a conceptual design configuration of equipment and operations which satisfies these requirements. This study was performed by Serendipity Associates, Chatsworth, California, for the Jet Propulsion Laboratory of the California Institute of Technology, under JPL Contract 951313. Results of the study indicate that (1) Serendipity's general method of systems engineering provided a relatively effective approach to develop a Remote Control Station design concept, (2) remote real-time control of spacecraft functions can be accomplished from an integrated mission-independent control complex, (3) real-time control requirements are most demanding for spacecraft imaging, positional, and locomotive state changes, (4) the mission planning as well as the ground-control system management functions must be dynamic, (5) classifying controls into one of three types allowed a relatively effective man-machine allocation, (6) an organizational structure provided a useful framework for assigning physical means, and (7) further design efforts are not merited without quantification of the complex man-machine interactions within and interfacing with the Remote Control Station.

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I. INTRODUCTION

The purpose of this report is to present the results of a thirty-two week study program conducted by Serendipity Associates for the Jet Propulsion Laboratory of the California Institute of Technology. Both the results and the approach used to obtain the results are presented. Rationale is provided wherever possible to allow evaluation of the validity of the approach and/or the results.

STUDY OBJECTIVES

The two major objectives for the project were to:

1. Develop and evaluate a systems-analysis technique applicable to the development of a conceptual design for a remote control station for use with the DSN.
2. Develop a conceptual design for a remote control station for use with the DSN.

The intent of the first objective was not to develop an entirely new technique, but rather to modify (if necessary) Serendipity's general systems-analysis technique to fit the needs of the project.

A critical aspect of the second objective is a definition of conceptual design. A conceptual design can exist at varying levels of specificity. The level assumed to be a necessary product of this project is that level which will specify (1) configuration or arrangement of functions comprising the system, (2) performances required of each function in functional (not physical) terms, (3) classes of hardware and personnel assigned to meet the requirements of individual or groups of functions, and (4) the physical relationship of the various classes of hardware and personnel (means). The conceptual design will not include design specifications wherein specific quantitative values for all major parameters must be provided at both the system and end-item level.

SCOPE OF THE PROJECT

This study consisted of the following three major activities:

1. Modify as necessary and document the study method and analytical techniques used.
2. Derive functional requirements for the Remote Control Station (RCS).
3. Develop a conceptual design to implement the functional requirements for the RCS.

Control of the spacecraft is required throughout the mission, i.e., from prelaunch checkout to collection and transmission of scientific data. However, all phases of the mission should not be treated equally from an analytical point of view, since (1) certain phases are essentially common to all missions and the approach in use currently is satisfactory (e.g., prelaunch checkout), and (2) on-board automatic control is an accepted and satisfactory approach to certain other phases (or portion thereof). Therefore, the study concentrates on the real-time remote-control aspects of scientific-data collection and direct support functions. Prelanding functions are not covered.

Contingencies resulting from malfunctions were also excluded from the study. However, contingencies resulting from change of conditions (either from external or internal sources) are covered.

The object system (i.e., the system to be controlled) is limited to unmanned, scientific spacecraft systems anticipated to be in operation during the 1966 to 1973 time period. A generic system is used as an object system (rather than a specific system such as the SURVEYOR), representing a composite of capabilities of different space vehicles. A generic spacecraft is admittedly more difficult to analyze due to data voids, but such would be more useful to JPL since an RCS designed to support a generic spacecraft should be more mission independent than an RCS designed for a specific spacecraft.

The means of transmitting and receiving signals were not considered in the study, although these means might have a significant impact on real-time control.

The study included analysis of data-collection objectives to define the basic requirements for a

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generic spacecraft system, functions analysis of the generic spacecraft system to determine spacecraft functions requiring (or amenable to) real-time remote control, functions analysis of selected segments of the ground-control system, and conceptual design of means (hardware and personnel) to meet the functional requirements.

REPORT ORGANIZATION

All the requirements information is presented in chapter II. As in the case of conceptual design, requirements for systems exist at varying level of detail. In this study, there are requirements at the overall system level encompassing both the spacecraft and ground segments, as well as for major segments of the overall system.

The overall system (defined as supersystem in chapter V) is basically a scientific data-collection system comprised of numerous sensors, a spacecraft to support and move the sensors, an earthbound segment to control the spacecraft and/or sensors, and an earthbound system to record and analyze the data. The basic requirements for this system are expressed in chapter II in the form of data-collection objectives (table 2-2).

The second level of requirements is presented in the form of spacecraft state-change requirements. These requirements identify the performances required of the spacecraft and its sensors to collect the necessary data. These requirements are presented in the form of Functional-Flow Logic Diagrams (FFLDs in figures 2-5 through 2-12) and supportive tables (tables 2-4 through 2-9) which describe in greater detail the types of performances required of the spacecraft.

The third level of requirements is specific to the RCS. The basic requirements for the RCS are presented in the form of a tabular listing of command/control requirements (tables 2-11 through 2-17) which essentially define the various classes of commands and/or controls for which the RCS is responsible. The command/control requirements were obtained by synthesizing the spacecraft state-change requirements and reexpressing the requirements in terms meaningful for determining what the RCS must be capable of accomplishing.

The final level of requirements is again specific to the RCS and defines in qualitative terms the state changes the RCS must go through in order to meet all the command/control requirements. These RCS state-change requirements are termed functional requirements since each pair of input and output states defines a function and its basic requirement. The functional requirements are presented in the form of FFLD (figures 2-14 and 2-15) and tables (table 2-19) which define, in somewhat more detail, the performances required of each function. The FFLDs represent a functional schematic of the RCS system design concept at the grossest level of detail, and the tables present the qualitative requirements for each function shown in the schematic.

The remaining sections of chapter II are concerned with the problem of deriving quantitative requirements for the RCS. We were not able to derive quantitative requirements during this study. Thus, the discussion is limited to the need for establishing quantitative requirements and how the requirements can be derived.

It is important to recognize that the requirements are presented at varying levels of detail, not in one single package. Each level is derived from the next higher level and depends not only on the requirements at the next higher level, but also on assumptions and judgments which guide the derivation process. The requirements can be presented in one single package but this would make it difficult to relate elements in the package to the approach described in chapter V.

The system design concept at the basic means level (hardware, personnel, etc.) is presented in chapter III. As indicated previously, the FFLDs for the RCS represent a functional schematic of the system design concept. Thus, the concept had to be developed before the FFLD could be developed. In other words, the lower-level requirements presented in chapter II constitute part of the system design concept. The design concept presented in chapter III is an extension of the concept presented in functional terms in chapter II and is presented in means terms. The concept at this level of detail specifies the types of means assigned to the system, the role each type is to play, and the relationship (both functional and physical) between the means. To simplify discussion, the system design concept at the means level will be termed the conceptual design of the system.

The conceptual design in chapter III is presented in two basic parts. The first part presents the organizational structure for the system. The structure is considered to be an integral part of the conceptual design since it provides a framework for the assignment of personnel tasks and thereby establishes a framework for the arrangement of equipment with which the personnel will have to interact.

The second part of chapter III presents the basic means assigned to implement the functional requirements. Both equipment and personnel are identified only by types or classes, not by specific individuals or specific equipment items. Assignment of specific individuals or equipment items would be premature at this time.

An equipment type by RCS function matrix is provided to show the role of each equipment type in each RCS function. A series of block schematics show the functional and basic physical relationship between the equipment types. A general workstation layout is provided to show the physical arrangement of the means.

The conclusions and recommendations resulting from the study efforts required to develop the materials for chapters II and III are presented in chapter IV.

Chapters II and III are designed to meet the second study objective, i.e., a conceptual RCS design. Chapter V is designed to meet the first objective and provides a description of the approach and techniques used to develop the conceptual design. Where possible, references are made to specific products in chapter II or III. The description emphasizes the general approach and shows how adjustment of the general approach were made either for or because of the study.

This chapter is organized into five major segments: General Requirements and Constraints (for the total data-collection system), Spacecraft State-Change Requirements, Remote Control Station Requirements, Quantitative Analysis Requirements and a recommended approach for conducting a quantitative analysis.

The first three segments are the major requirements segments of the report and relate directly to the conceptual design in chapter III. The requirements segments describe a general set of data-collection objectives assumed to be relevant to the spacecraft systems to be supported by the RCS, the basic state changes required of the spacecraft systems to meet the data-collection objectives, and the performances required of the RCS to properly support the spacecraft systems to meet the necessary data-collection objectives.

The total data-collection system of which the remote control station (RCS) and the spacecraft are members, also includes a network of tracking stations (DSIF), a ground communication system (a part of NASCOM) and a centralized operation complex (SFOF). The basic objective of this total system is to collect scientific data at lunar or planetary distances. The above-mentioned major elements comprising the system must all act in concert to attain the data-collection objective. Being part of the same system, and working towards the same objectives, the major elements are interdependent. The requirements for one major element, such as the RCS, cannot be oonsidered independent of its relationship to the other elements.

To place the specific requirements for the RCS in proper context, the objectives of the total system are defined first. These objectives are defined at a fairly gross level, but the definition provides a base for deriving and discussing RCS requirements. The data-collection objectives, though necessary, are not sufficient to allow derivation of RCS requirements. The basic data collector is the spacecraft and the sensors it carries. The performance characteristics of the spacecraft and its sensors define the support required of the RCS. Thus, the basic characteristics of a generic spacecraft system are described next.

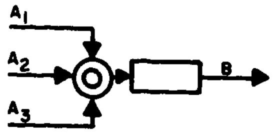
The requirements for the RCS are defined in functional terms, subsequent to a description of the spacecraft systems the RCS must be able to support. The limited time available for the study prohibited derivation of quantitative requirements. Thus, the discussion is limited to a need and an approach for deriving quantitative requirements.

SYMBOLS AND TERMS

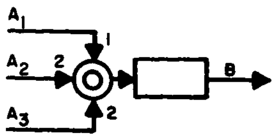
Definitions of key terms are provided in chapter V in the discussion of the approach. Since functional-flow logic diagrams (FFLDs) are used to present state-change requirements in this chapter, brief definitions of those terms required to interpret the diagrams are presented in this section. Symbols used in the diagrams are also defined in this section.

◎	And (All)
⊕	And/or (one, all, or any combination)
⦶	Either/or (one and only one)
⟶	State—a set of qualities which describes a form of existence.
⟶[	Input state—the set of qualities which must exist before an element of performance (function) can be initiated.
]⟶	Output state—the set of qualities which when achieved completes an element of performance.
▭	Function—an element of performance bounded by input and output states.
[ ]	An interacting function, not a part of the selection or system under analysis.

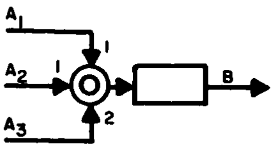
Special symbol designating a state as information or command.



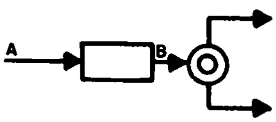
All three input states are required before the function can be initiated and completed, i.e., provide output state B.



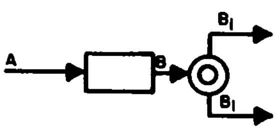
Only input state A_1 is needed to initiate the function but input states A_2 and A_3 are required to complete the function.



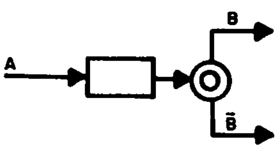
Input states A_1 and A_2 are required to initiate the function but A_3 is also required before the function can be completed.



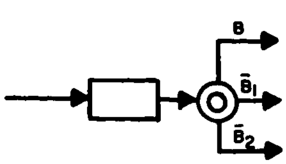
B is the output state but has two destinations.



B is the output state comprised of sets B_1 and B_2, each having a different destination.



B is the required output state; $\bar{B}$ is a NOT state which may occur (generally adverse to the main objective), but is not a required state. The NOT states usually require corrective action, or a function to return the system to some previous state.



B is the required output state comprised of sets B_1 and B_2. $\bar{B}_1$ is a NOT state of the B_1 set and B_2 is a NOT state of the B_2 set.

A symbol frequently used to show the destination of an output state.

A symbol frequently used to show the source of an input state.

GENERAL REQUIREMENTS AND CONSTRAINTS

The general requirements and constraints in this section refer to the requirements and constraints for the total system, rather than any specific portion, such as the spacecraft or the RCS. In our terminology, requirements can be expressed only in terms of state changes, which necessitates an input and an output state to be defined. Constraints are limitations on the means which can be used to effect the necessary state change.

A general requirement for the system can be expressed symbolically, as shown in figure 2-1 (See ground rules 1 through 4, chapter V, section on Establishing System Requirements).

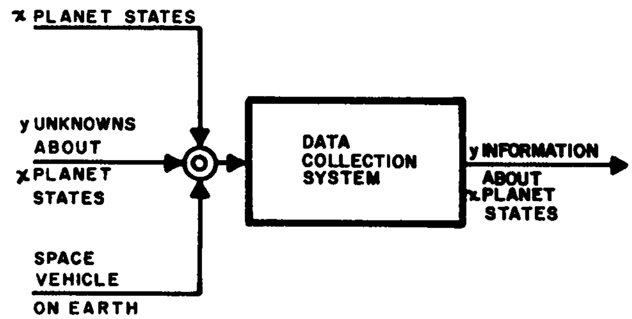


Figure 2-1. Basic state-change requirement.

The initiating condition for the system is a given number (x) of planet states about which certain facts are not known (y unknowns). The third input state (i.e., space vehicles will be used to collect data and the system must include the performances required to transport the spacecraft to the planet of concern. The output state is achieved when the unknowns are changed to knowns.

Simple as the diagram may be, it helps nevertheless to establish the basic boundaries for the system, and provides a foundation for further definition of states. The diagram helps to establish the basic state class (ground rules 2 and 3) which needs to be expanded and a basic constraint on system means (ground rule 6); i.e., space vehicle as the basic data-collection means.

More specific boundaries of the system can be ascertained by first determining the planets about which information is needed, and, subsequently, determining the areas of unknown about the selected planets. Since space vehicles are assumed to be means limitations, it will also be necessary to specify the types of space vehicles which are to be used as data collectors. This could become a horrendous task, far exceeding the scope of the study, unless some constraints are established. The constraints presented below are based on (1) an attempt to limit the study to a reasonable scope, (2) information provided by JPL on forthcoming space probe programs, and (3) what appeared to be a reasonable lifetime for the RCS system.

CONSTRAINTS

1. The useful lifetime of the system is limited to from six to eight years. Rapid advancements in both space vehicle design and electronic equipment would probably make the RCS system obsolete in about six to eight years. Attempting to design a system with a longer life at this time probably would not be cost effective, especially when one considers a two- to three-year lead-time in acquiring the system.

2. The system will be operational approximately two years after initiation of detailed system design—system definition phase.

3. The spacecraft systems to be included (supported by the RCS) will be those currently envisioned for the 1968-1976 era. Candidate spacecraft systems are SURVEYOR, ORBITER, MARINER, ROVER, unmanned APOLLO, and VOYAGER. The missions of concern to the project are those designated to investigate certain properties of the moon, Mars, and Venus. Although in-transit investigations may be conducted, this project will be constrained to the on-station (on-planet) portion of the mission.

4. It will be assumed that the DSN at the time the system becomes operational will not be significantly different from the current DSN.

5. The basic physical configuration of the system will be as depicted graphically in figure 2-2 (ground rule 6).

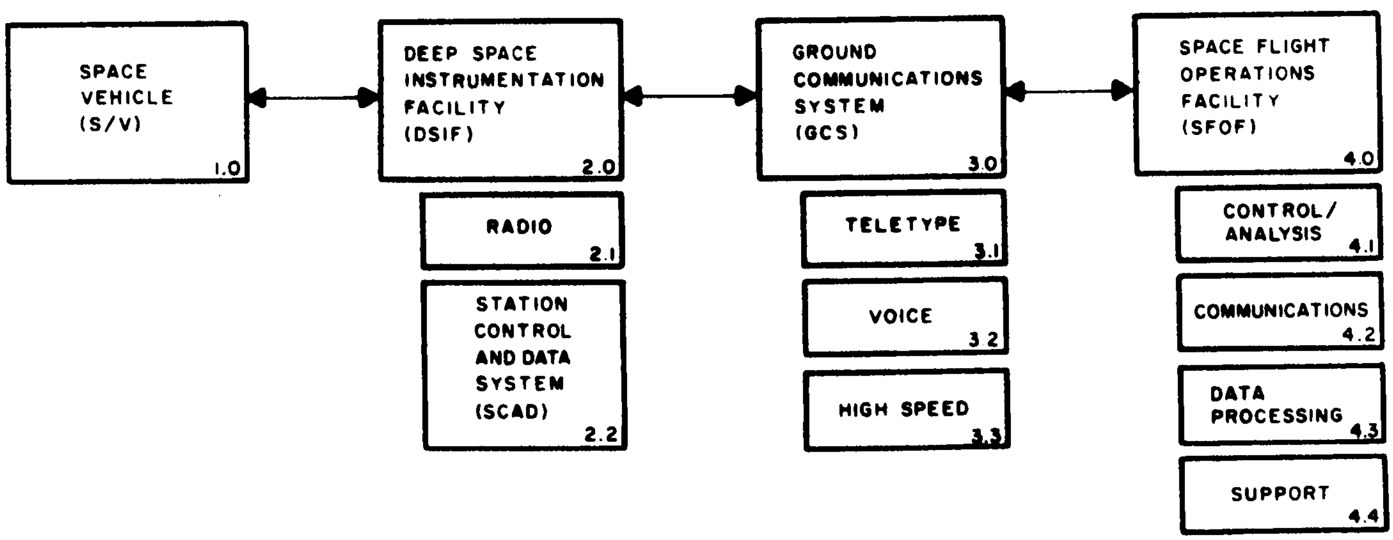


Figure 2-2. Data-collection system block diagram.

The spacecraft will communicate via a deep space instrumentation facility (DSIF) and general communications system (GCS) with the spaceflight operations facility (SFOF). The RCS will be a part of block 4.1, control/analysis. All system elements, with the exception of the spacecraft and the RCS, will be treated as intervening elements through which information flows, is transduced, and/or is processed.

6. The spacecraft and associated sensors to collect the data will be constraints for the total system. Since the RCS must be able to support a multitude of missions on different spacecraft systems, most of which have not been designed yet, the specific constraints imposed by the spacecraft and/or sensors cannot be ascertained at this time. However, the variety per se indicates that the design of the RCS must be flexible to allow it to meet different requirements for different missions even when they occur concurrently.

Although the specific question of sensors to be used for individual missions cannot be answered at this time, the magnitude of this constraint is indicated by an examination of one set of candidate means hypothecated by JPL (Speed, et al., Tech. Memo. No. 33-241, 1965) for a stationary spacecraft operation on the moon. This set is presented in table 2-1. As indicated, many of the data-collection techniques require that sample preparation, deployment to the surface, or other manipulative activities be performed. It is expected that similar experiments will be incorporated into the mission profile of a spacecraft designed for planetary investigation. The particular technique that is ultimately selected to take a set of measurements affects the specific requirements for control of that mechanism. The variation in control requirements may originate from the sensor characteristics, i.e., its sensitivity to thermal, acoustic, and pressure variations. The control requirement will vary if it requires deployment, positioning, or unique conditioning. In general, the set of sensors, regardless of the experimental techniques selected, will require the alteration of certain physical conditions relative to them. These alterations may be positional, thermal, electrical, etc.

The allocation of control responsibilities will depend on the design of specific spacecraft systems. It is doubtful that the RCS designers can dictate the allocation to spacecraft system designers. However, it is anticipated that the allocation will depend to a large extent on the control capabilities in the RCS. Thus, it is assumed that most of the control functions will be allocated to the RCS.

DATA-COLLECTION OBJECTIVES

The data-collection objectives discussed in this section are an expansion of the planet (x) and information (y) state-change requirements indicated in a gross manner in figure 2-1 (ground rule 4). The state parameter of concern is information about

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Table 2-1. Possible Experimental Techniques for Stationary Lunar Spacecraft.*

Priority	Measurements	Experimental techniques	Space hardware development status	Completeness of data and technique limitations	Precision and accuracy	Additional measurements contribute to or adaptable to	Major incompatibilities with other instruments and/or s/c bus	Accessories or special handling requirements	Time req. for measurement, min
1	Phase analysis	X-ray diffractometer	Prototype	Quant. data, any grain size	Mod–high	Elements, volatiles	Requires high power	Sample prep., or deployment	30
		Polarizing microscope	Breadboard	Grain size dependent, qualitative	Mod–low	Texture, fabric	None	Sample preparation	5
		High resolution reflected light images	Prototype	Very qualitative, grain size dep.	Low	Texture, fabric	None	Deployment	5
		Differential thermal analyzer	Feasibility	Unable to resolve many individual phases.	Low	Volatiles	Heat generator	Sample preparation	(30)
		Infra-red spectrometer	Feasibility	Severe sample preparation requirements		None	None	Sample preparation	?
		Luminescence spectrometer	None	Unproven technique		None	None	Sample preparation	?
2	Seismic surface net	Seismometer (single-axis)	Flight	Short period and single axis limit depth and direction determining ability	Mod	None	Affected by vibration	Firm mechanical coupling with lunar bedrock	Continuous
		Seismometer (three-axis)	Prototype	Multi-axis allows azimuth determination	High	None			Continuous
3	Rock texture	Petrographic microscope	Breadboard	Grain size dependence	Mod–high	Phases, fabric	None	Sample preparation	5
		High resolution reflected light images	Prototype	Coarse grain rocks only	Mod–high	Fabric	None	Deployment	5
		Penetration drill	Breadboard	Very qualitative, ambiguous	Low	Density	Vibration, reaction force against bus	Deployment	<10
		Sieves	None	For particulate rocks only	Low	None	Vibration, dust agitation	Sample scooper	(10)
5	Rock fabric	Surveillance television	Flight	Color differentials by filters	High	Topography	None	Boom mount for stereo	Continuous (1 sec/frame)
		Close-up stereo TV		Requires good lighting	High	Texture	View obstruction by bus	Dual lens or boom mount for stereo	Continuous (1 sec/frame)
6	Surface geometry	Surveillance television	Flight		High	Fabric, texture	None	Color filters	Continuous (1 sec/frame)
7	Major element analysis	X-ray spectrometer	Prototype	High sensitivity matrix effects; requires powder sample	Mod	None	e/m background	Sample prep. or deployment	30
		Alpha scatterer	Flight	Variable sensitivity poor resolution of K and Cu, iron & nickel	Low	None	Radioactive source	Sample prep. or deployment	180
		X-ray diffractometer	Prototype	Good data if crystalline; limited if glass	Low–mod	Phases, volatiles	None	Sample prep. or deployment	30
		Neutron activation	Breadboard	All elements, time-dependent, source problems	Mod	None	Sample becomes intensely radioactive	Sample prep. or deployment	30
		Gamma-ray spectrometer	Flight	Detects natural radioactives (K^{40}, U, Th) and cosmic ray induced Na, Al, Fe	Low	Radio isotopes	Must be away from bus to minimize bus interference	Requires boom mount	Continuous
		Petrographic microscope	Breadboard	Requires coarse grain crystalline material	Low	Phases, texture	None	Sample preparation	5
		Visible emission spectrometer	Feasibility	Critical and complex sample preparation required	?	None	?	Sample preparation	?
		Mass spectrometer (solids)	Breadboard	No sample preparation required with sputtering ion type	?	Vocatiles, atmosphere	Magnet	Sample preparation	?
		Wet chemical (discrete reactor)	Feasibility	Separate reactor device for each element	Low	None ?	?	Sample preparation	?
		Neutron inelastic scatterer	Feasibility	Limited to several elements (Fe, Mg, Al), low sensitivity	Low	None	Radiation	Deployment	?
		Polarography device	None	Requires electrochemical solutions good only for base metals	Low	None	None	Critical sample prep.	
9	Natural radioisotopes	Gamma-ray spectrometer	Flight	No sample preparation necessary	High	None	Away from bus	Boom mount	Continuous
		Ionization chamber		Poor resolution	Low	None	None	None	Continuous
		Mass spectrometer (solids)	Feasibility	Complex sample preparation required	Low	Elements	Magnet	Sample preparation	?
		Film dosimeter	None	Low resolution	Low	None	None	None	
		Scintillation dosimeter	None		Low	None	None	None	

(Cont'd)

* Taken from Speed, et al., JPL Tech. Memo. No. 33-241, 1965.

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Table 2-1. (Continued)

Priority	Measurements		Experimental techniques	Space hardware development status	Completeness of data and technique limitations	Precision and accuracy	Additional measurements contribute to or adaptable to	Major incompatibilities with other instruments and/or s/c bus	Accessories or special handling requirements	Time req. for measurement, min
4	Surface density (bulk)		Gamma-gamma backscatter	Breadboard	Simple. Requires deployment, sensitive to surface irregularities	Mod	None	Radiation	Deployment	10
			Scale (wt of known vol)	None	Crude; requires disrupting surface	Low	None	None	Deployment	10
10	Atmosphere	Total pressure	Ionization gage	Feasibility	Simple; not mass dependent	High	None	Sensitive to outgassing bus	None	Continuous
			Mass spectrometer (gas)	Breadboard	Mass range 12–66	High	Volatiles, elements, atmosphere	Magnet, bus contamination	None	Continuous
			Bourdon tube	Feasibility	Insensitive to high vacuum	Nil	None	None	None	Continuous
		Composition and partial pressures	Mass spectrometer (gas)	Breadboard	Mass range 12–50	High	Volatiles	S/C contamination, magnetic		Continuous
			Gas chromatograph (inorganic)	Prototype	Insensitive to exterior low pressures	Low	Volatiles	S/C contamination	Carrier gas	Continuous
			Photon absorption	Feasibility	Requires extreme path length. Could utilize moon–earth telemetry signal	Nil(?)	None	None		Continuous
			Discrete chemical reactors	Feasibility	Insensitive to low concentrations	Low	Volatiles	None		Continuous
11	Subsurface Body Configuration		Short-period seismic detector	Prototype	Requires known baseline distance to source	Mod	Seismicity	None	Surface coupling	Continuous
			Explosive charge(s)	Feasibility	Requires emplacement away from s/c	—	None	Shrapnel damage to S/C	Deployment projectiles	?
8	Volatile constituents		Multistep heater (DTA)	Feasibility	Simple. Requires some sample preparation and connection to gas analyzer	High	—	Heat dissipation	Sample preparation	30
			Gas chromatograph (inorganic)	Prototype	Less sensitive to inorganic gases	Low	Atmosphere	None	Sample preparation	60
			Thermogravimeter	None	No specie resolutions	Low	None	?	Sample preparation	?
			Mass spectrometer (gas)	Breadboard	Mass range 12–66	High	Atmosphere	None	Sample preparation	Continuous
			Discrete chemical reactor	Breadboard	Separate reactor for each gas specie limits resolution	Mod	Atmosphere	None	Sample preparation	Continuous

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planet states which is not available at this time. Data are the intermediate criteria for information.

It is quite difficult to specify all data-collection objectives at this time since the unknowns about planet states vary with time, ongoing projects, and scientists. Yet, some bounding of unknowns is required at least to establish the general population of data which will (or may) be required to be collected by spacecraft systems controlled by the RCS.

Ideally, the boundaries should be established after thoroughly interrogating all relevant space system planners and JPL scientists. Because of time constraints, we chose first to establish the general boundaries and data-collection objectives, using available JPL documents as source data. If necessary, the results could then be checked by cognizant personnel. The data-collection objectives presented below are the result of the above approach and have not been checked in detail by cognizant personnel. A detailed check or interrogation of JPL scientists was not conducted since (1) the objectives, though gross, served the purpose of establishing the necessary boundaries for the system, and (2) more accurate and detailed data probably would not be any more useful until we attempt to derive quantitative requirements and relationships.

As implied above, the basic purpose of defining the data-collection objectives is to define in somewhat more detail the state changes required of the total data-collection system. These definitions are necessary to allow useful partitioning of the system, especially if the partitions depend on the data types. That is, if different system functions are required to collect different types of data, it is important that the data types be differentiated at the outset. Conversely, detailed classifications beyond the level required to partition the system would not be useful at this time.

The candidate data-collection objectives were classified in terms of the basic properties of the universe, such as force fields, radiation, and matter. Since these phenomena may occur at various locations in the universe, domains of investigation were identified as space, atmosphere, surface, and subsurface. Investigation is concerned with either the static or dynamic conditions of the properties within these domains. General data-collection objectives were classified by basic property and domain of investigation. This classification is presented in table 2-2.

Each cell in the Classification of Data Collection matrix represents a generalized scientific data-collection objective. The letter in the designator refers to the basic property for which data are being collected, and the arabic numeral identifies the conditions of the area within the domain of the investigation. Specific spacecraft objectives can be identified in the cells. This is illustrated by inserting experiments planned for SURVEYOR in cells B5, C5, E4, E5, E8, F1, and F5.

Table 2-2 represents the top-level requirement for the total data-collection system. The sources of variance entry in the table represents a further qualification of the data-collection objectives. The data represent measurements of the properties. These measurements are assumed to have a distribution. The mean and/or variance of the measurements is assumed to vary in accordance with factors such as location on the terrain, atmospheric conditions, etc. These are termed sources of variance since they are the factors which contribute the largest portion of the total variance for the property of concern and, therefore, will probably be taken into account in designing experiments for specific missions.

The term "natural variance" refers to a property or condition that is not directly under measurement but may affect a property that is being measured. For example, the surface density will undoubtedly vary with the location of the spacecraft. Therefore, terrain unit is designated as a source of variance which needs to be measured also. Other examples of natural variances are presented in table 2-3. Data in these entries are considered necessary to permit interpretation of data on basic property measurements.

Another basic source of variance consists of factors which affect the mechanisms used to collect and transmit the data. These other sources must be considered also since they affect the interpretation of the data. Thus, they represent another source of data requirements since engineering and calibration data will be required by the experimenters to assure that the scientific data are meaningful. It is assumed that both natural and mechanism sources of variance will be considered in designing experiments for individual missions.

Table 2-2, Classification of Data-Collection Objectives.

Environmental Categories	Basic Properties*	Domain of Investigation							
		Space		Atmosphere		Surface		Subsurface	
		1 - Static	2 - Dynamic	3 - Static	4 - Dynamic	5 - Static	6 - Dynamic	7 - Static	8 - Dynamic
Force Fields	A. Gravity Magnetic Electrostatic			1 - 2	1 - 2	1 - 2	1 - 2	1	1
Radiation	B. Electromagnetic Charged Particle	4	4	1-2-3-4	1 - 2 - 4	1 - 2 - 4	1 - 2 - 4	1	1
Matter	C. Chemical Composition Structure			1 - 2	1 - 2	Alpha Scattering 1 - 2	1 - 2	1	1
	D. Electrical Conductivity Magnetivity			1 - 2 - 3	1 - 2	1 - 2	1 - 2	1	1
	E. Mechanical Density Strength Elasticity			1 - 2 - 3	Micrometeorite 1 - 2	Soil Mechanics Touchdown Dynamics 1 - 2	1 - 2 - 5	1	Seismic 1
	F. Geometry Size Shape			1 - 2	1 - 2	Television Soil Mechanics Touchdown Dynamics 1 - 2	1 - 2 - 5	1	1
	G. Thermal	4	4	1 - 2 - 4	1 - 2 - 4	1 - 2 - 4	1 - 2 - 4	1	1

* Property variance (not variance of data-collection process)

A measured property is not considered a source of variance of itself. The following sources of variance apply to properties being investigated, and are identified by numbers in data-collection cells where appropriate:

1 - Terrain Unit
2 - Atmospheric Activity
3 - Meteoroid Flux
4 - Radiation Flux
5 - Seismic Activity

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Table 2-3. Examples of Sources of Natural Variance. *

Source of Variance	Examples of Variance
1. Terrain Unit	Vulcanism; Radioactive deposit; Variations in density, slope, roughness, composition, etc.
2. Atmospheric Activity	Precipitation; Suspended particles; Winds; Clouds, etc.
3. Meteoroid Flux	High velocity particulate matter.
4. Radiation Flux	Solar radiation; Cosmic radiation; Thermal radiation; Surface radioactivity, etc.
5. Seismic Activity	Surface slides; Sub-surface disturbance; Thermal shock, etc.

* A source of variance is not considered to affect itself when it is the property being measured.

PARAMETERS FOR QUANTIFICATION

Sufficient data are not available to assign quantitative values to the general system requirements at this time. However, the parameters to which values must be assigned eventually have been identified and are defined briefly below (ground rule 5):

1. Time:—length of time required to gather an adequate sample of data, assuming that data collected will vary as a function of time.

2. Quantity:—the amount of continuous data, or the number of discrete data points required to indicate significance, assuming that data collected will vary as a function of distribution.

3. Quality:—the level of purity of data, or the amount and type of contamination permissible that will still indicate significance, assuming that certain data, either by nature of the property or the inherent inadequacies of the sensor, may be ambiguous.

The above parameters are the basic parameters for the data-collection requirements of the system. It may not be possible to allocate quantitative values to each criterion due to lack of consensus on the need for individual data sets. However, any intermediate criteria used must be directly related to the above three criteria.

REQUIREMENT CONSIDERATIONS AFFECTING SYSTEM DESIGN

The extent to which the cost effectiveness of system segments or elements can be proven or predicted quantitatively will depend on the extent to which meaningful quantitative values can be assigned to the parameters. If no value is assigned, it will not be possible to assess quantitatively the merit of any design decision in terms of its contribution to the total system. There will be no assurance that the subsystems will be compatible. If quantitative values are established only at the subsystem level, the tendency will be to suboptimize at the subsystem level without any assurance that this will be optimal for the total system. Experience on other systems indicates that the greatest subjective weight will be given to engineering judgments.

The lack of quantitative values does not mean that lower-order requirements cannot or should not be derived. As indicated in chapter V, it will be necessary first to derive lower-order requirements before quantitative values can be derived. However, the lower-order requirements in turn may change when quantitative values are assigned. It is important to recognize this process of change through iteration since the primary impact of the changes will be on changes of physical means. Apparently small changes in lower-order requirements could have a significant impact on the physical means.

Another aspect of the requirements which must be considered in system design is the representativeness of the data. As indicated previously, it is assumed that an experimental design will be developed eventually for each experiment to be included in each flight. The comprehensiveness of the design undoubtedly will vary with individual experimenters, but the system must be prepared to meet the needs of the most sophisticated experimenter. The experimental design will not only specify the sources of variance to be covered, but also the sampling technique, the number of data points, supportive data, and the experimental hypothesis to be tested.

Identification of the potential sources of variance is an important step in anticipating the type of experimental designs which may be imposed on the system. Most important, the sources of variance help to identify critical spacecraft state changes such as changes of location and position. In addition, the need to measure the representativeness of data for data-interpretation purposes generates the need to consider the collection of data on related factors, including engineering variables.

SPACECRAFT STATE-CHANGE REQUIREMENTS

As previously indicated, the sensors selected for data collection, and the subsystems required to support those sensors, must undergo changes of state to accomplish their objectives. A change in state may be specific to the sensor, such as change of gain, change of stability, on-off state, etc. In addition, there are state changes which appear to be supportive, such as change of position or location, change of internal temperature, change of power outputs, etc. These and other changes of state relevant to both the environment in which the sensor is located as well as the relationship of one subsystem to another are required in the data-collection process.

These changes of state are intermediate state changes required to effect the major data change of state discussed in the previous section. Defining these intermediate state changes should define a more specific set of command/control requirements for the RCS. Since the sensors and spacecraft designs are means constraints for the system, it will be necessary to limit the detail at which the intermediate state changes are defined. If the intermediate state changes are defined at levels specific to a given sensor or spacecraft, the RCS will also be specific to a particular spacecraft or sensor. Thus, the intermediate state changes must be at a level applicable to all the spacecraft systems which are to be supported by the RCS.

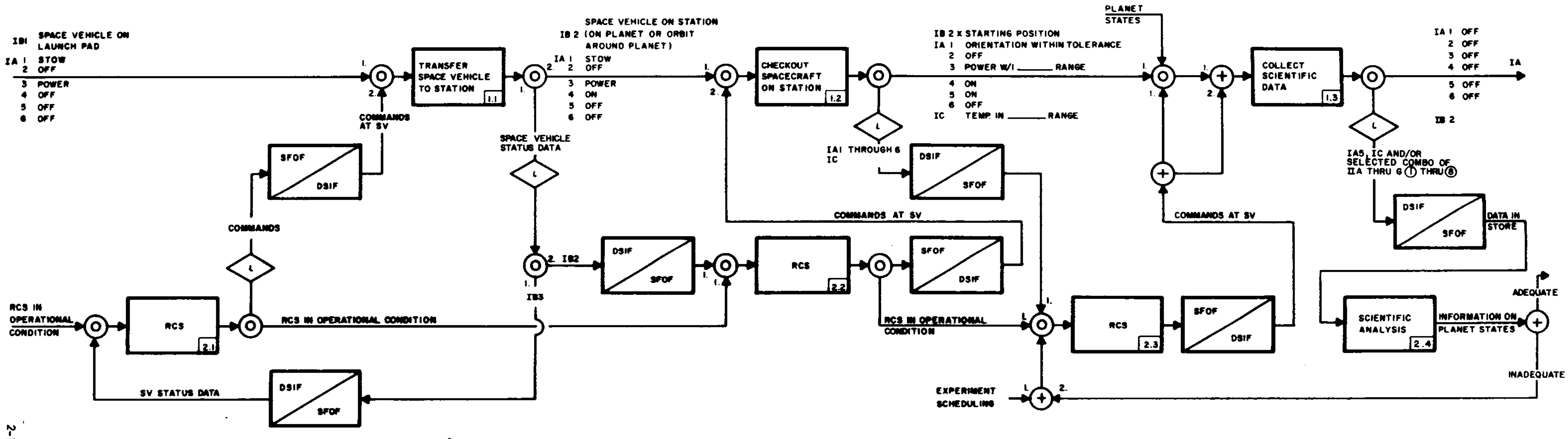
In our terminology, the intermediate state changes define the boundaries for functions. The functions can be defined at varying levels of specificity. At very low levels of detail they tend to be similar to design specifications and therefore are equipment-oriented. To maintain a generic set of spacecraft state changes, the functions defined in this section are at a fairly gross level.

The spacecraft state changes are defined at three levels in this section. The first, or top-level, partitions the total system into major functions, considering the constraints discussed in the previous section. The second level partitions one of the major functions which is the function directly responsible for data collection. The third level partitions the specific function identified in the second level as being specifically responsible for data collection. The more specific requirements of all the functions identified at the second level are presented in tabular form. These functional requirements are the major product of this section since they provide the basis for the command and control requirements for the RCS discussed in the next section.

TOP-LEVEL STATE-CHANGE REQUIREMENTS

The top-level state-change requirements are presented in a functional-flow logic diagram (FFLD) in figure 2-3 (See ground rule 9). Since the blocks represent functions, the diagram represents a functional composition of the data-collection system shown in the same form in figure 2-1. This initial partitioning of the total system was governed by the data-collection objectives shown in table 2-2, the basic system-level means constraints shown in figure 2-2, and a general mission profile shown in figure 2-4.

The general mission profile identifies the basic functions required to transfer the space vehicle from Earth to its destination. Since these functions are already identified in the mission profile and are not



LEGEND:

I SPACE VEHICLE PHYSICAL STATES
- A. CLASSES OF MEANS
  - 1 CONFIGURATION CONTROL
  - 2 PATH CONTROL
  - 3 AUXILIARY POWER
  - 4 INFORMATION TRANSFER
  - 5 ENVIRONMENT CONTROL
  - 6 SCIENTIFIC DATA GATHERING
- B. LOCATION
  - 1 EARTH
  - 2 STATION AREA (NON-EARTH)
  - 3 IN FLIGHT
- C. ENVIRONMENT

II PLANETARY STATES (SEE TABLE A)
- A. FORCE FIELDS
- B. RADIATION
- C. CHEMICAL
- D. ELECTRICAL
- E. MECHANICAL
- F. GEOMETRIC
- G. THERMAL

DOMAINS OF INVESTIGATION
- (1) SPACE, STATIC
- (2) SPACE, DYNAMIC
- (3) ATMOSPHERE, STATIC
- (4) ATMOSPHERE, DYNAMIC
- (5) SURFACE, STATIC
- (6) SURFACE, DYNAMIC
- (7) SUBSURFACE, STATIC
- (8) SUBSURFACE, DYNAMIC

- ◎ AND (ALL)
- ⊕ AND/OR
- ⦶ EITHER/OR
- ◇ INFO. OR COMMAND STATE
- → STATE
- □ FUNCTION

FIGURE 2-3. SPACE VEHICLE FUNCTION FLOW LOGIC DIAGRAM.

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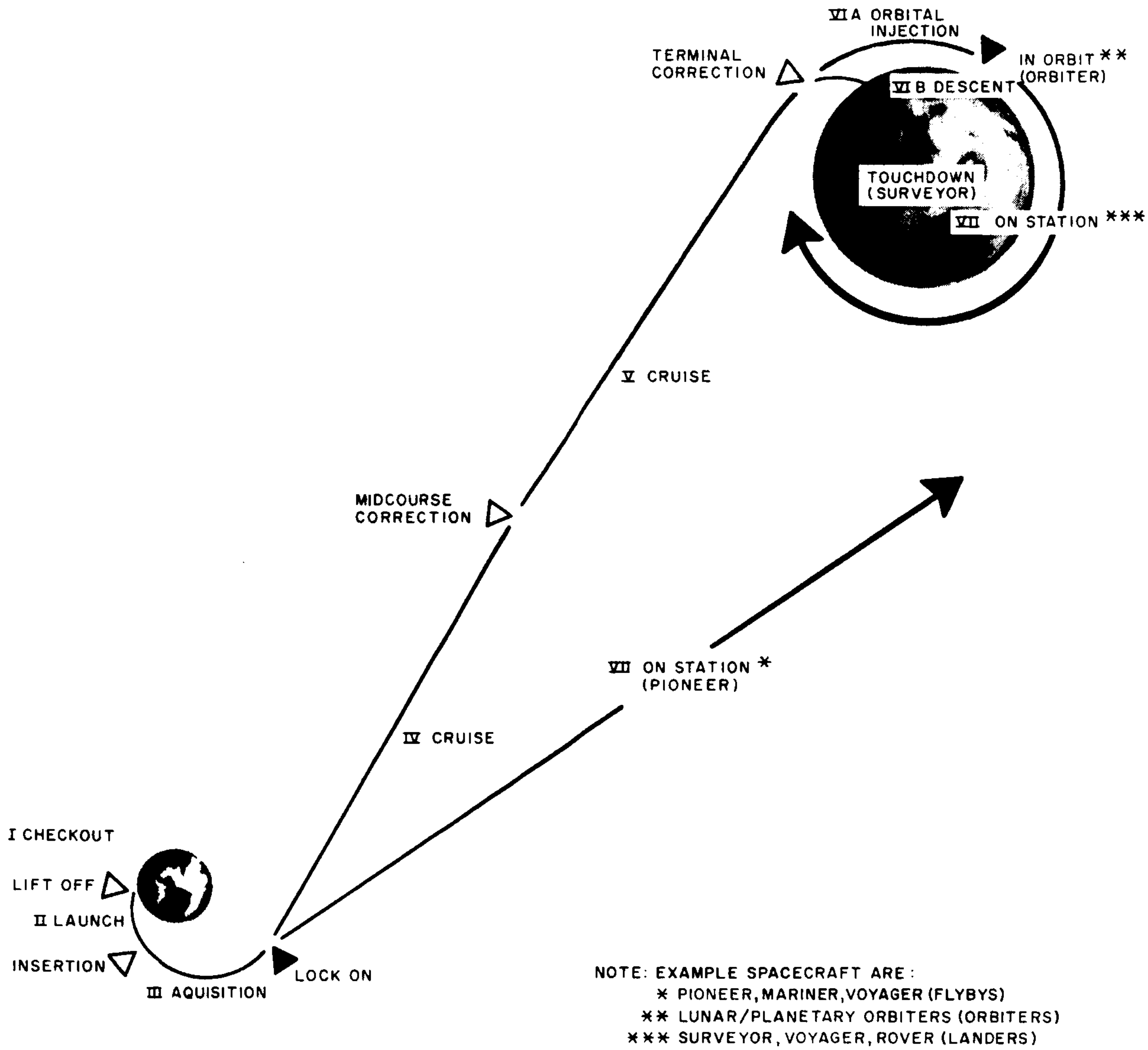

Figure 2-4. General mission profile.

of major concern to the study, they are incorporated into one function in the FFLD in figure 2-3. In fact, the FFLD concentrates on the on-station function (VII) in the mission profile.

The code numbers refer to parameters which change state within the system. The basic classes of parameters are space vehicle states and planetary states. With respect to the latter, the concern is with the data which reflect planetary changes of state. The domains of investigation are further substates of planetary states of concern. The space vehicle states are further divided into classes of means, location of the space vehicles and environment within the space vehicle. The classes of means are based on assumed means which in turn are based on the type of data-collection techniques presented in table 2-1 as well as various other JPL documents. The SFOF/DSIF and RCS blocks represent different untitled functions which are necessary if (1) the state changes are to be all-inclusive and (2) the remote control concept is to be shown.

Function 1.1 starts with the space vehicle on the launch pad (IB 1) with its set of means essentially in an OFF mode (IA1 through IA6). Note that this state represents the same state as "space vehicle on earth" state in figure 2-1. Function 1.1 cannot complete its function (i.e., provide the necessary output state) until it receives commands from the RCS via the SFOF/DSIF. In turn, the RCS (2.1) cannot provide the commands unless it receives data on the status of the space vehicle, especially during flight (IB3). Until the major output state (2) is reached, the status will be provided by 1.1 via the DSIF/SFOF. The data are used in 1.1 to determine the commands to send. Function 1.1 will be complete when the space vehicle is on station, and the means are in the specified state.

The output state which completes function 1.1 is required to initiate function 1.2, but the function cannot be completed until the proper commands are received from function 2.2. Since the purpose of function 1.2 is to put the spacecraft in a state ready for data collection, the RCS can provide the necessary commands on the basis of state data received from function 1.1.

When the spacecraft is in the proper position (IB2), the means are in the proper state (IA1 through 6) and the environment is within tolerance (IC), the system is now ready to collect data on planet states under the control of the RCS (2.3). The RCS will provide the commands on the basis of the state at the completion of 1.2 and either the a priori experimental schedule or status data from 1.3.

Function 1.3 will provide the necessary data (IIA3, 4, etc.) and turn the system off. Note that function 1.3 does not provide the final output state specified in figure 2-1. This state is provided by the scientific analysis (2.4) function which determines whether the information is adequate. Note also that no separation is made for different missions. Completion is defined only in terms of data sets. The system undoubtedly will require multiple missions, both in series and parallel.

The role of the RCS is specified in this figure, then, as a subsystem that is required to monitor the performance of the data-collection process, issue commands to change the state of the spacecraft and/or a specific data sensor, and determine when the performance requirements have been met in terms of data sufficiency.

MAJOR STATE CHANGES FOR COLLECTING SCIENTIFIC DATA

Only one function in figure 2-3 is directly concerned with collecting scientific data, i.e., function 1.3. Since the primary concern for this project is the control of data collection, only this one major function is analyzed further (ground rule 9).

The major state changes required for collecting scientific data are presented in figure 2-5. Figure 2-5 shows the spacecraft in position on the surface ready to receive various commands. The particular command(s) initiates a specific function (depending on the situation) required to support the Collect Scientific and Engineering Data function (1.3.6). The control is effected by closing the loop with the RCS via the Transfer Information function (1.3.4 and 1.3.5). It should be noted that the diagram is limited to the functions within the spacecraft necessary to effect the state changes required to meet the data-collection objectives.

At the initiation of the data-collection process, it is assumed that the spacecraft is on-station (indicated by IB2), the sensors are in proper position,

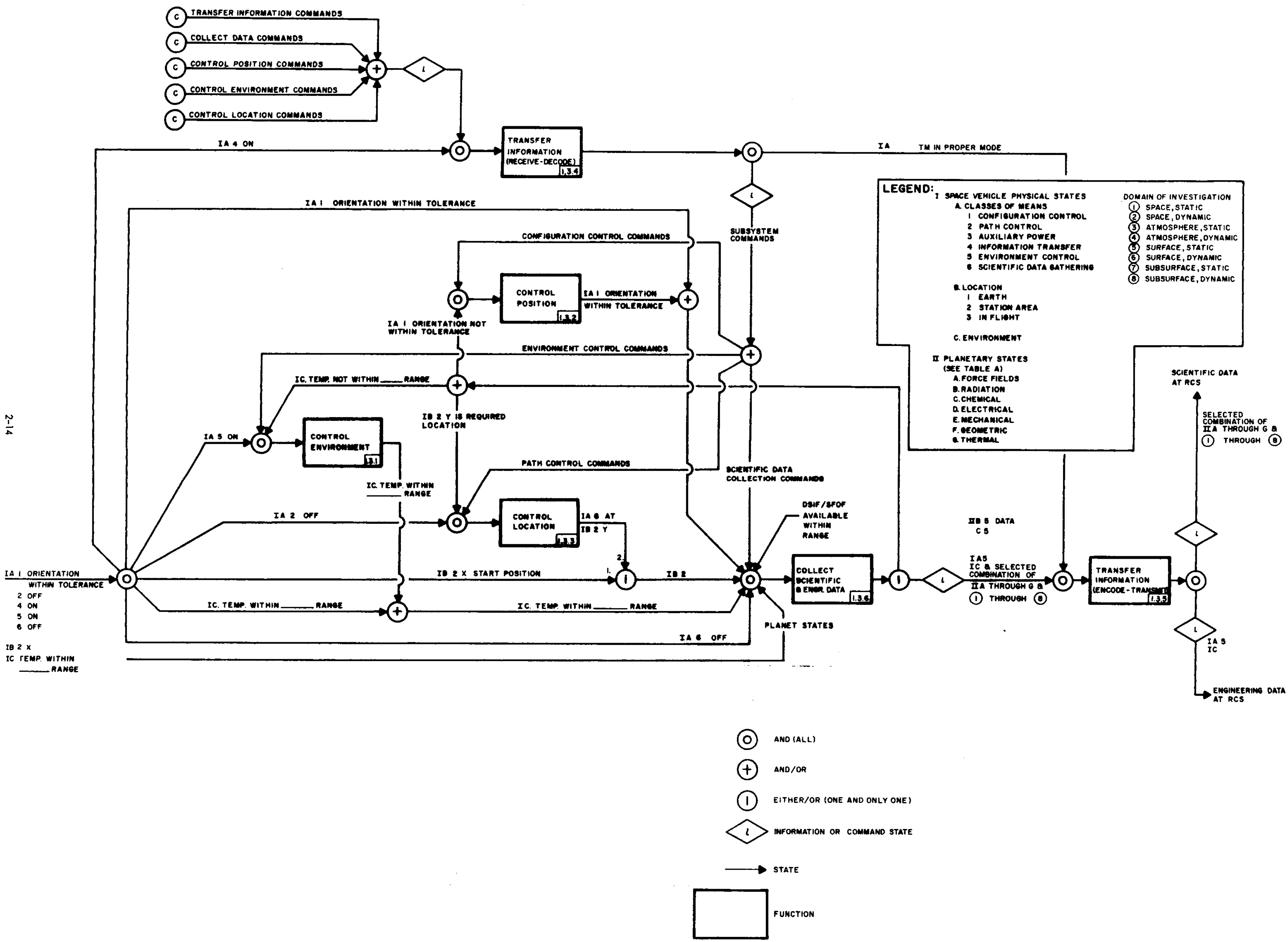

FIGURE 2-5. FUNCTIONAL FLOW LOGIC DIAGRAM OF THE COLLECT SCIENTIFIC DATA FUNCTION (1.3).

(IA1 within tolerance), flight guidance, propulsion, etc. are no longer needed and are turned off (IA2 OFF), the telecommunications system is operative (IA4 ON), and the data-collection sensors are not energized (IA6 OFF). Commands are received via the Transfer Information function (1.3.4) to change the state of the environment, position, location, and/or the data-collection devices. The resultant data is transferred via function 1.3.5 to the Earth. This process is continued until the specified information state is reached, or an adverse or NOT state is reached which cannot be altered.

Note that function 1.3.6 requires seven input states before it can meet its state-change requirements. Three of these states concern environment, position, and location. Since one of the requirements for function 1.2 (see figure 2-3) is to satisfy these three state requirements, there should be no need to change states before 1.3.6 can be initiated. However, degradations of the internal environment can be anticipated while data are being collected. In addition, it is assumed that new sensor positions or locations will be required before all the necessary data can be collected. Thus, the basic requirement for functions 1.3.1, 1.3.2, and 1.3.3 arises from anticipation of adverse or NOT states in 1.3.6.

It is important to note that the required output state for function 1.3.6 is the specified data state, not the adverse or NOT state. The NOT states are likely contingencies which create a need to change states to allow the function (1.3.6) to meet its required state. NOT states can only occur when the function is in process, and the continued existence of a NOT state will prevent the function from reaching the required state. Thus, functions 1.3.1, 1.3.2, and 1.3.4 are supportive functions which are required only when the environment goes out-of-tolerance (1.3.1), or the sensor or configuration is not at the required orientation (1.3.2), or the location of the spacecraft and/or the sensor is not at the required location (1.3.3).

The level of detail to which figure 2-5 was taken depended primarily on the major contingencies identified for function 1.3.6 which, in turn, depended on the input state classes identified for the system in figure 2-3. The FFLD in figure 2-5 could have been developed at a lower level of detail, but this was not necessary since it served the purpose of identifying areas which should be analyzed in greater detail, or, conversely, areas which need not be analyzed further.

Since all the functions in figure 2-5 are in support of 1.3.6, it is apparent that the detailed requirements for all other functions at this level can be determined by analyzing only the data-collection function, i.e., 1.3.6. Furthermore, examination of data available from previous studies on central functions indicated that (1) we could not advance the state of knowledge of control by further analyzing the control functions at this time, and (2) the area requiring expansion is the relationship between data collection and the control functions. Thus, only function 1.3.6 was analyzed further.

DATA-COLLECTION STATE CHANGES AS DEFINED BY EXPERIMENT TYPES

This final level of spacecraft state-change analysis was conducted to help (1) identify the specific relationship with the control functions and (2) determine the extent to which the command/control requirements varied with experiment types.

In order to analyze function 1.3.6 further, it was necessary to consider the various types of experiments which would require different data sets. To serve the purpose of defining relationships, it was necessary to examine the various types of sensors which might be used in these experiments. To limit the scope of the analyses to a level commensurate with the time and manpower constraints of the project, the analysis was limited to those cells in the data-collection objectives matrix (table 2-2) which were represented by SURVEYOR experiments. The results are presented in figures 2-6 through 2-12.

Figure 2-6 illustrates a function to measure static radiation at the surface of the moon or planets. The required input states are both informational and physical. Control signals which may be required to control this function are indicated as commands. Typically these signals are required by a sensor which performs this function. The commands then are considered as information to be provided to the function. Prior to acceptance of the control signal, that is, before the desired data can be gathered by the function, certain physical states of the sensor must be provided. These are shown as conditions necessary to initiate the function. Should any of the

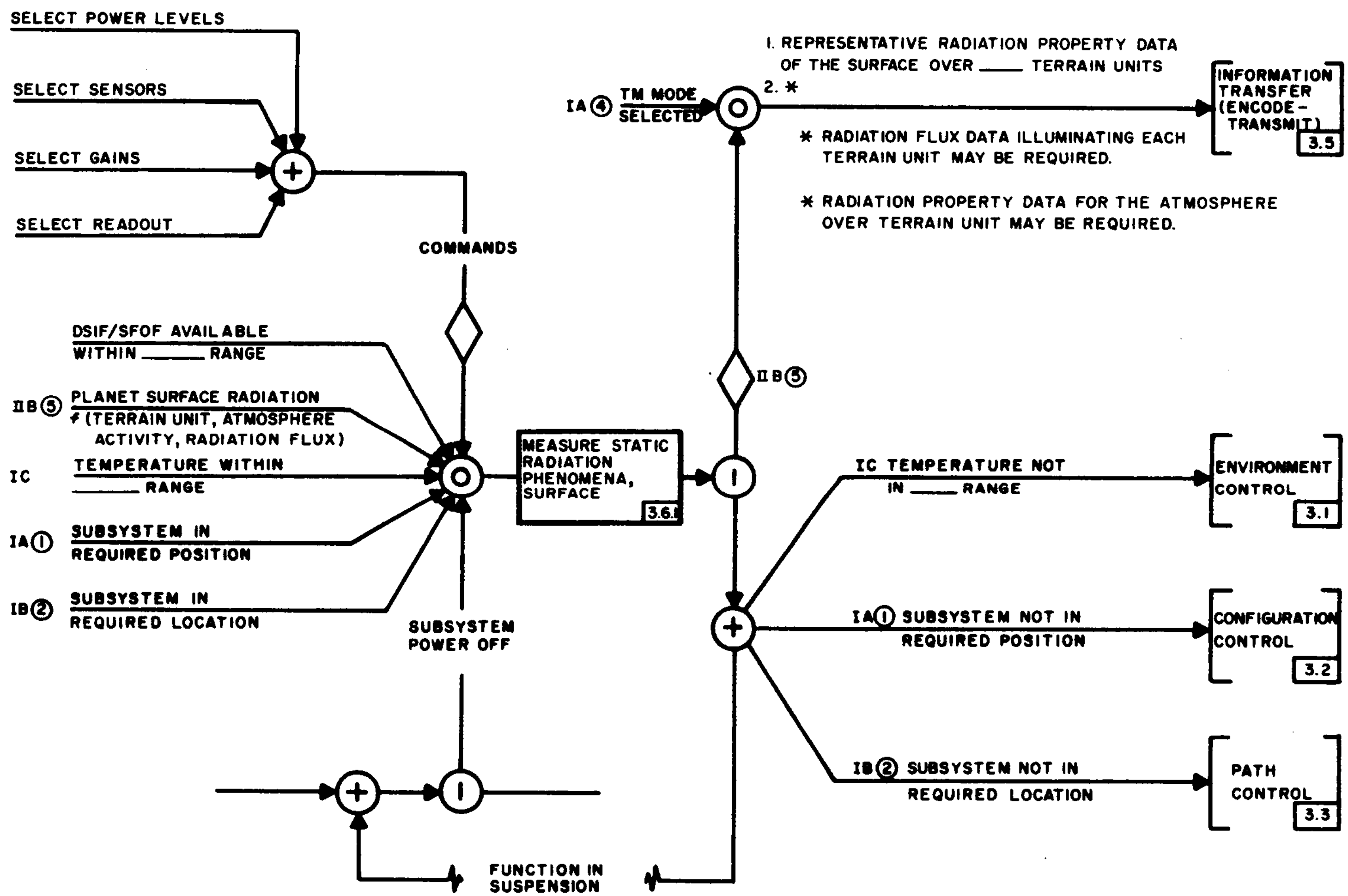

Figure 2-6. Level 3. Function 1. 3. 6. 1 measure static radiation phenomena, surface.

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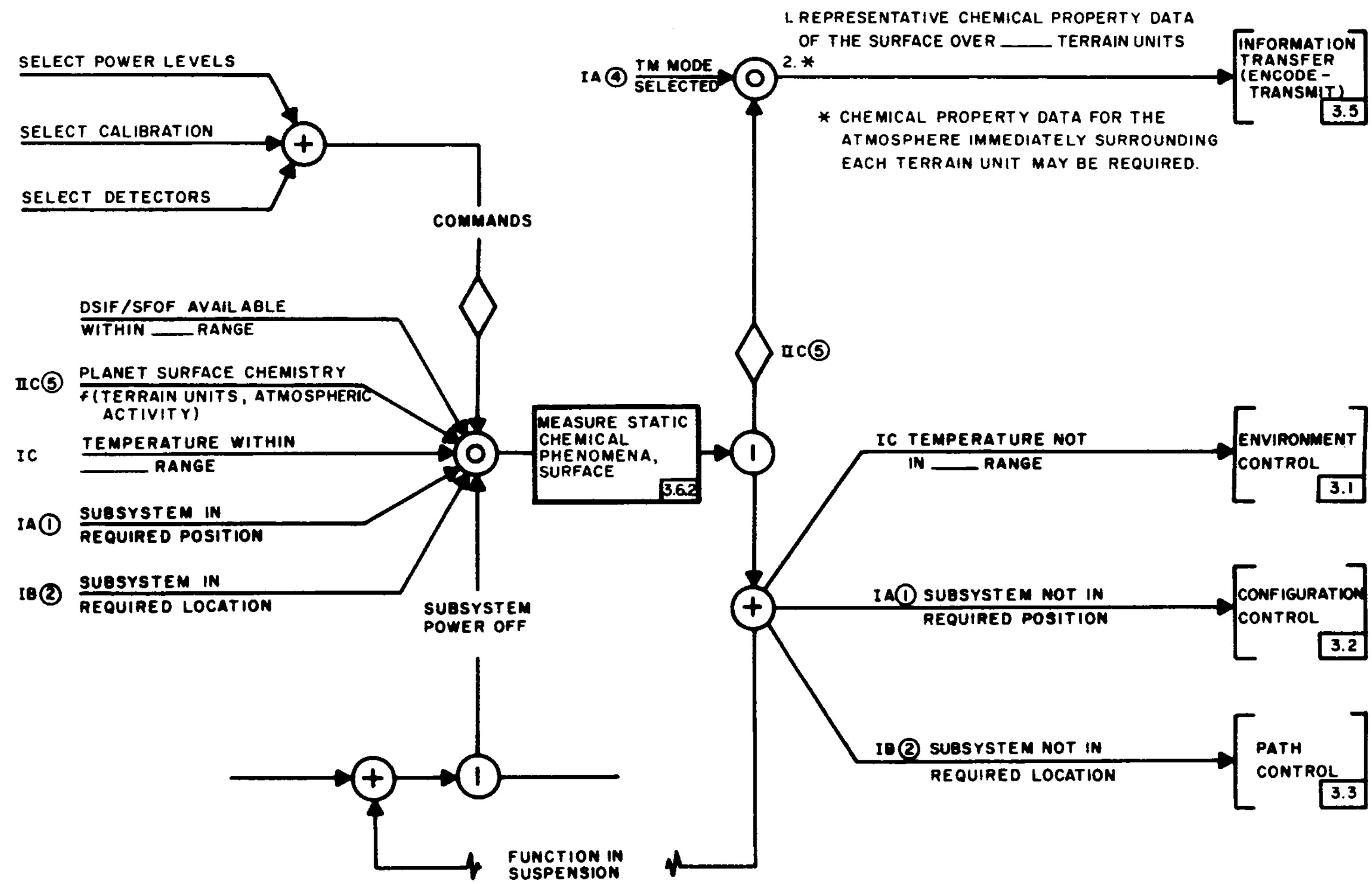

Figure 2-7. Level 3. Function 1.3.6.2 measure static chemical phenomena, surface.

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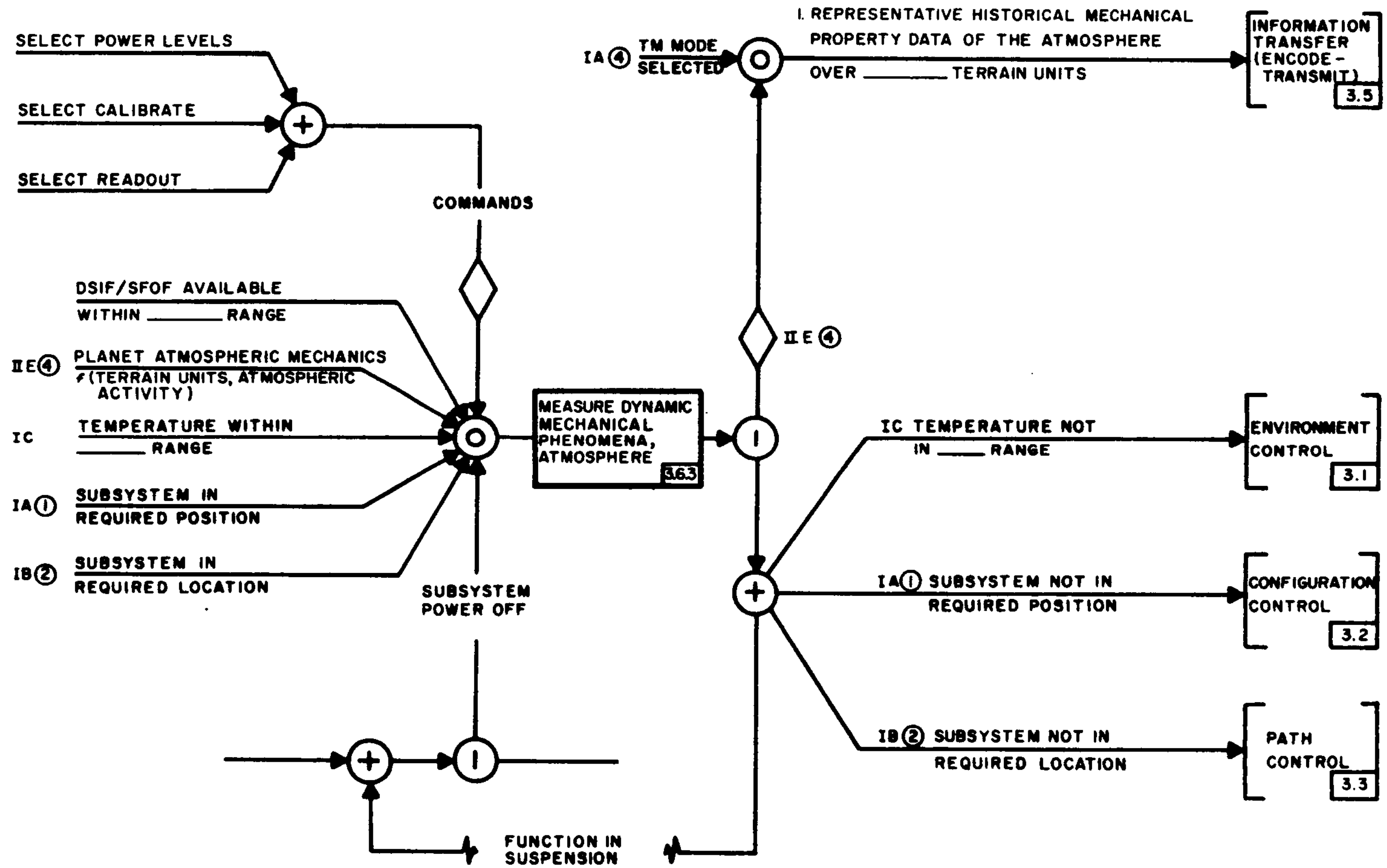

Figure 2-8. Level 3. Function 1.3.6.3 measure dynamic mechanical phenomena, atmosphere.

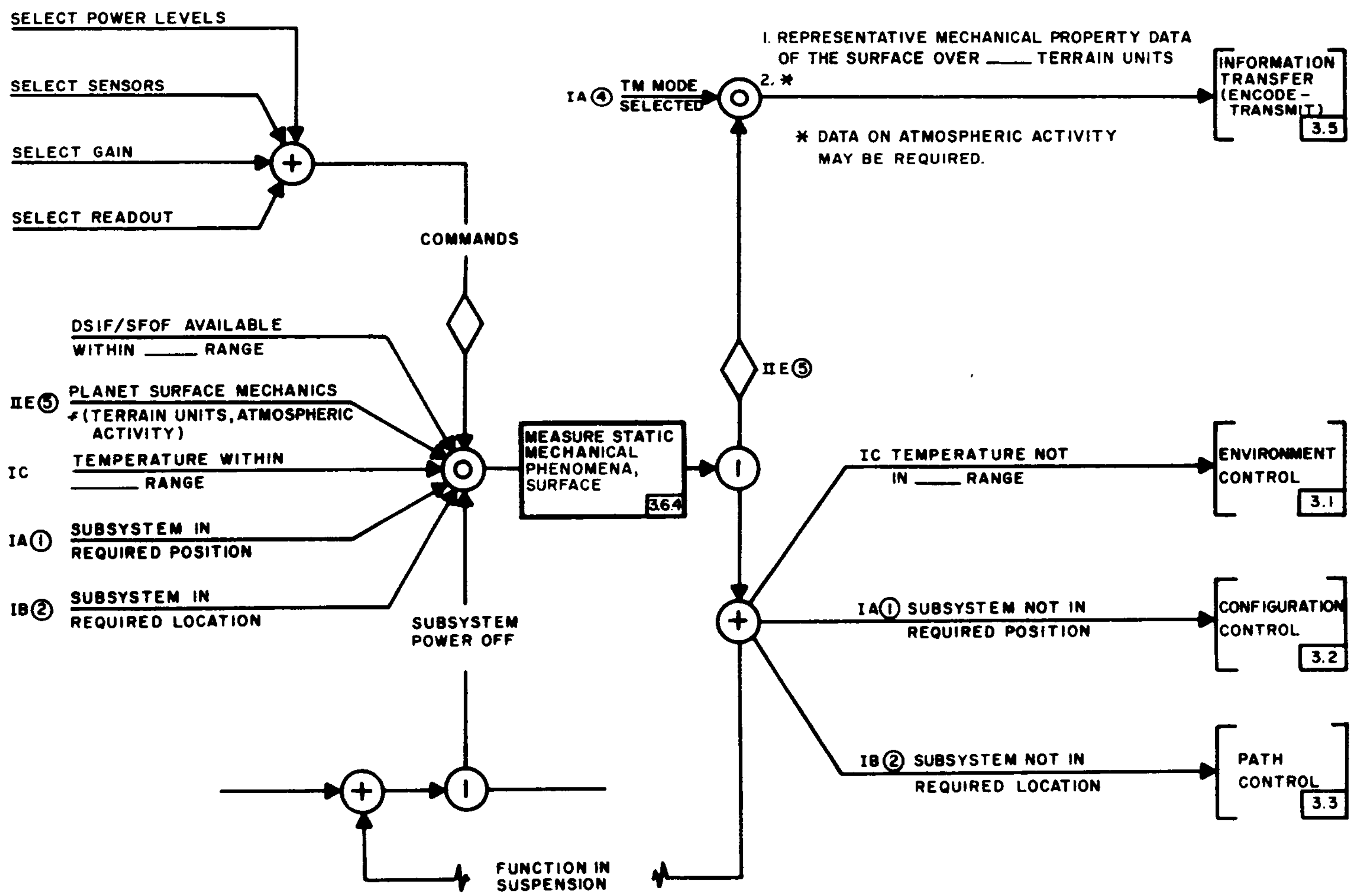

Figure 2-9. Level 3. Function1.3.6.4 measure static mechanical phenomena, surface.

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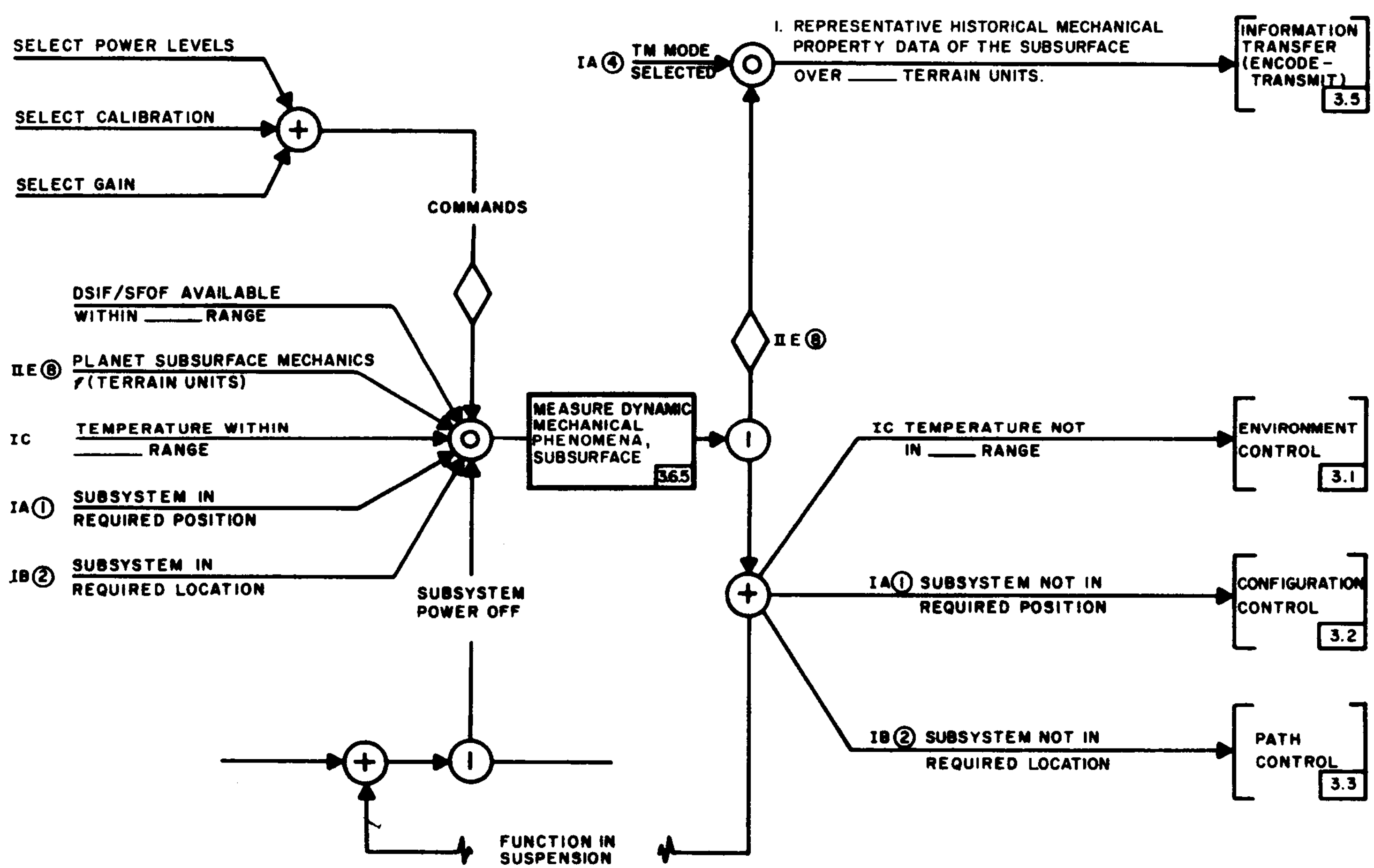

Figure 2-10. Level 3. Function 1. 3. 6. 5 measure dynamic mechanical phenomena, subsurface.

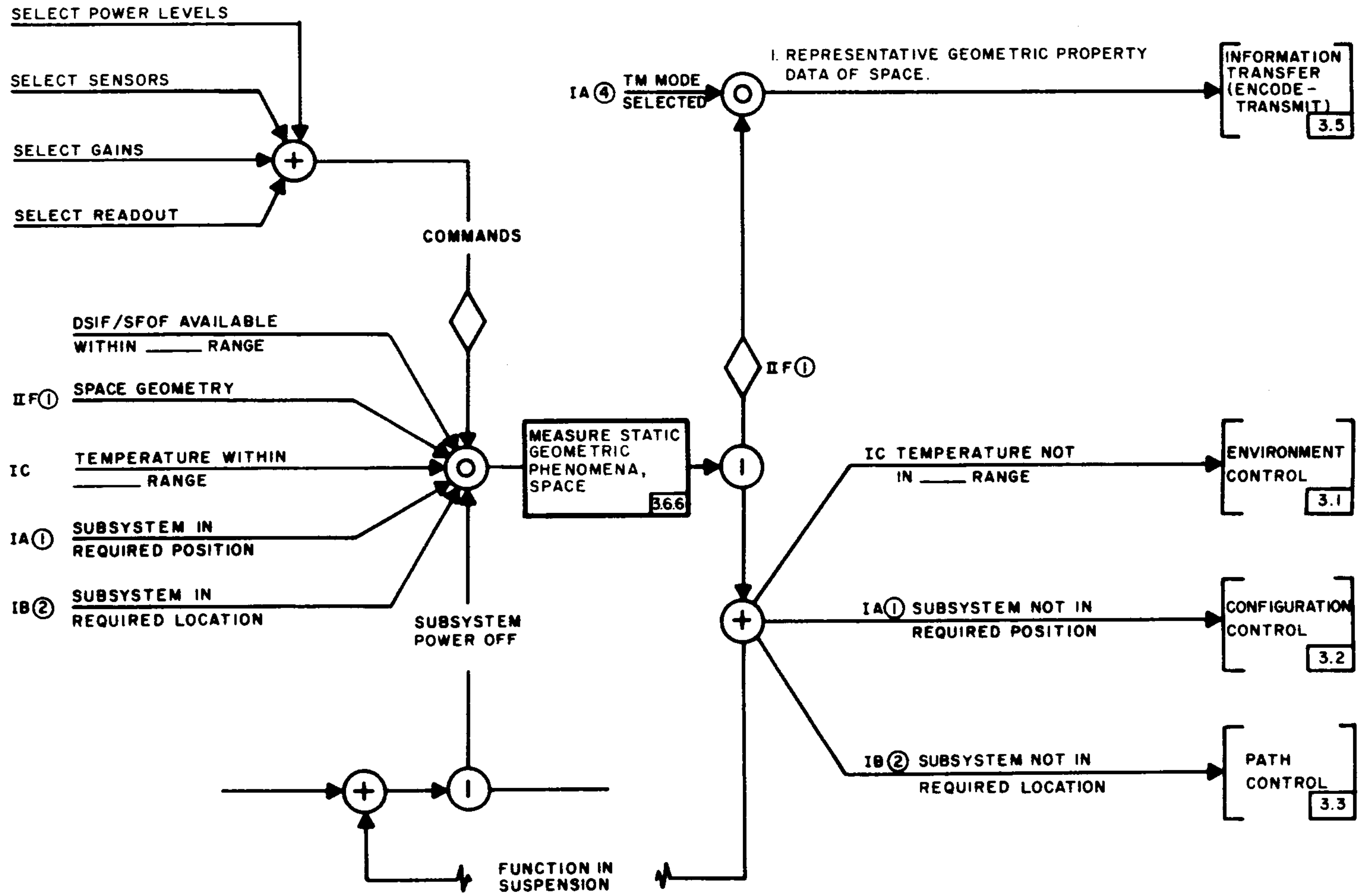

Figure 2-11. Level 3. Function 1. 3. 6. 6 measure static geometric phenomena, space.

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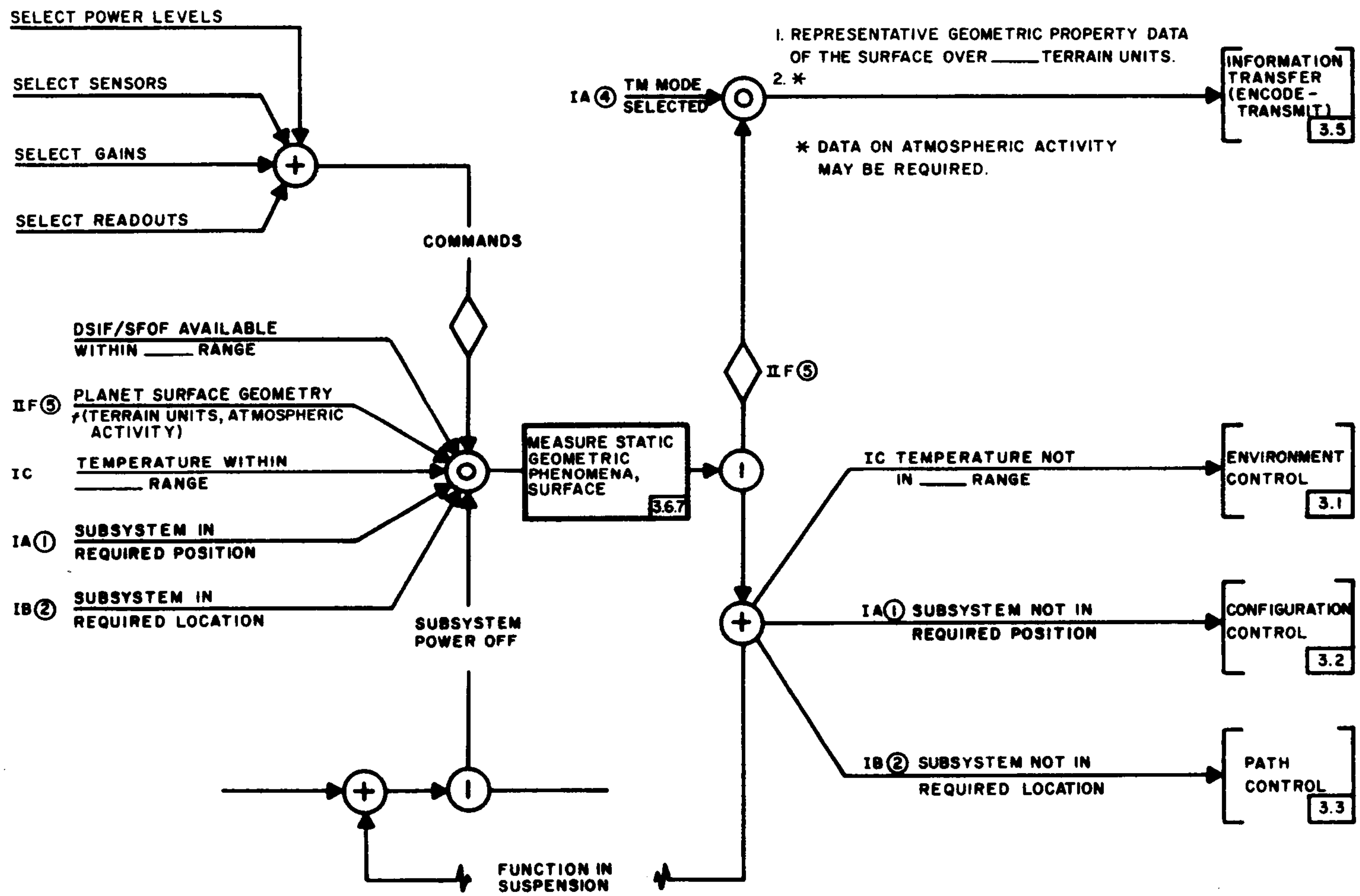

Figure 2-12. Level 3. Function 1. 3. 6. 7 measure static geometric phenomena, surface.

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adverse states occur, as indicated by the output state of the function showing objective not completed, a supporting function is called upon to correct the adverse state. Inability to provide the necessary correction decreases the probability of achieving the desired data. Should a higher-priority function, or a support function, require the interruption of the specific data-collection function, the function is considered to be in suspension until such time as it can be resumed to complete the data objectives.

One further analysis was conducted, but the results are not presented in this report due to inconclusive results. It is worthy of mention, however, since it indicated an avenue not worth pursuing further at this time. The analysis to this level still does not identify the specific commands required by any given set of equipment which may be designated for a given flight. To obtain an indication of the specific commands which might be required, 37 candidate sensors for seven experiments were analyzed. The results were inconclusive since there was no assurance that the 37 sensors were representative. Furthermore, the specific command requirements were still questionable since the commands depend on the allocation of controls to the RCS during sensor design.

The analysis did indicate though that it would not be cost effective to attempt to identify all possible sensors before the individual spacecraft systems are definitized. The potentially large variety of sensors involved and the variety of design decisions required to select the sensors for any single mission of a spacecraft system imposes a requirement on the RCS to be extremely flexible to allow changes from mission to mission. A factor critical to providing this flexibility are not the individual sensors so much as the characteristics (both common and unique) of the sensors. These characteristics must be defined before the RCS design is finalized, but do not need to be defined in detail to develop a conceptual design.

SPACECRAFT FUNCTIONAL REQUIREMENTS

As indicated previously, only the data-collection function (1.3.6) of figure 2-5 was partitioned further. However, all functions were analyzed to define more specifically the required performance characteristics of the functions in order to define the command/control requirements for the RCS. The specific purpose of the analysis was to determine the performances required within each function (regardless of where they are conducted), the factors that affect the performances, the range of performances, and the information required for the performance.

The partitioning of function 1.3.6 provided useful data for specifying the functional requirements for that function. The partitioning was useful in defining the differences in performance for different types of experiments. In previous partitioning, the control of power was treated as part of function 1.3.6. In view of the different type of performance involved, control of power is treated as a separate function in this section. In addition, the two information transfer functions were grouped together because of the similarity of performances.

The functional requirements presented in tables 2-4 through 2-9 are the product of all the spacecraft state analysis described previously. They should be reviewed within the context of the higher-level requirements described in previous sections. However, the requirements in the tables are the basic set of requirements towards which the RCS design is oriented.

The first column in the tables defines the various subsets or subclasses which comprise the class of concern (See ground rule 4). Thus, the scientific-data state class is comprised of three major substates, each of which is further divided into substates. These states refer to the output state for the function of concern. Column 2 identifies the parameters associated with each state subclass. These parameters may, in most cases, be treated as further definitions of the subclass. Where quantitative values are assigned, they will be assigned to the parameters identified in column 2.

The required states are specified in column 4. The requirement for the function is to reach the required state. The complexity of the performances will depend to a large extent on the other forces or factors impinging on the state parameter. Given no performance within the function, the values of the state parameters will still vary with time. Depending on the factors, the variations may be leading to, or away from, the required level. The factors expected to cause the major variations are listed in column 3.

Table 2-4. Functional Req¨irements for Collecting Scientific and Engineering Data (1.3.6)

State Class: Scientific Data

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Means	7 Expected Selection Range	8 Probable Control Type
A. Properties of Force Fields 1. Gravity 2. Magnetic 3. Electrostatic	Potential and polarity vs time in cm/sec^2, gauss, statvolts, etc.	1. Terrain Units 2. Atmospheric Activity 3. Meteoroid Flux 4. Radiation Flux 5. Seismic Activity	Representative Sample of the ______ property, as a function of ____ data points and ______ sources of variance	1. Present Selection of: a) Sensor power level(s) b) Sensor(s) c) Sensor gain(s)	1. Selection of proper: a) Sensor power level(s) b) Sensor(s) c) Sensor gain(s)	Binary/Multiple Binary/Multiple Binary/Multiple	II II II
B. Properties of Radiation 1. Electromagnetic 2. Charged particle	Energy density, energy distribution, intensity flucuations, velocity distribution, spatial orientation, etc.		$\frac{Dc}{Pr}$ changes with (1) Dc or as (2) Dr is revised based on information gained from Dc. (Dc = data collected Dr = data required)	2. Accuracy of sensor and associated electronics (as a function of natural degradation.)	2. Calibrate sensor(s)	Binary/Multiple	I
C. Properties of Matter 1. Chemical	a) composition b) structure c) distribution			3. Location of sensor relative to property sample	3. Place sensor in required relationship to property by: a) repositioning sensor b) relocating S/V	See analysis of: a) position state b) path state	
2. Electrical	a). conductivity b) magnetivity c) emissivity			4. Operating power to sensor and associated electronics	4. Adjust power input by: a) reposition solar array b) select other power source	See analysis of a) position state b) power state	
3. Mechanical	a) density b) strength c) elasticity			5. Temperature of: a) sensor b) electronics (causing artificial degradations)	5. Effect temperature change by: a) heating or cooling sensor b) heating or cooling electronics	See analysis of temperature state for: a) sensors b) instrumentation package	
4. Geometrical	a) size b) shape						
5. Thermal	a) conductivity b) absorptivity c) emissivity						

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Table 2-5. Functional Requirements for Controlling Environment (1.3.1)

State Class: Environment

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Techniques	7 Expected Selection Range	8 Probable Control Type
Sensor Temperature	1. Temperature 2. Rate of change of temperature	1. Power source variations 2. Heat transfer from other subsystems 3. Solar shielding	1. Temp. within survival range 2. Temp. within operational range 3. Sensor in thermal equilibrium with environment	1. Survival limits 2. Operational limits 3. Availability of power 4. Ambient temp. 5. Desire for sensor operation	1. Select proper heater setting 2. Adjust solar shielding 3. Regulate other heat sources 4. Regulate power source 5. Relocate sensor 6. Reposition S/C	Binary Binary/Multiple Multiple Multiple Binary/Multiple Multiple/Continuous	I II III II III III
Temp. of instrumentation package	↓	1. Power source variations 2. Heat transfer from other subsystems 3. Solar shielding	1. Temp. within survival range 2. Temp. within operational range	1. Survival limits 2. Operational limits 3. Availability of power 4. Need for system operation	1. Select proper heater setting 2. Adjust solar shielding 3. Regulate other heat sources 4. Regulate power source 5. Reposition S/C	Binary Binary/Multiple Multiple Multiple Multiple/Continuous	I II III II III
Propellant temp. 1. Oxidizer 2. Fuel	↓	1. Power source variations 2. Heat transfer from other subsystems 3. Solar shielding 4. State of depletion of tankage	1. Propellants in usable condition 2. Propellants in efficient operational range	1. Usability (not boiling nor frozen) 2. Operational efficiency 3. Safety (tank pressure)	1. Select proper heater setting 2. Adjust solar shielding 3. Regulate other heat sources 4. Regulate power source 5. Reposition S/C	Binary Binary/Multiple Multiple Multiple Multiple/Continuous	I II III II III
Pressurant Temperature	↓	1. Power source variations 2. Heat transfer from other subsystems 3. Solar shielding 4. Depletion of pressurant (a) usage (b) leakage	Temp. within operational range	1. Quantity of pressurant available 2. Desired pressure 3. Allowable temp. ranges of adjacent systems	1. Select proper heater setting 2. Adjust solar shielding 3. Regulate other heat sources 4. Regulate power source 5. Reposition S/C	Binary Binary/Multiple Multiple Multiple Multiple/Continuous	I II III II III
Battery Temperature	↓	1. Solar shielding 2. Heat transfer from other systems 3. Discharge rate	1. Temp. within operational range 2. Temperature within survival range	1. Power demands from other systems 2. Voltage requirements 3. Survival limits	1. Adjust solar shielding 2. Regulate heat sources 3. Reposition S/C 4. Regulate power consumption	Binary/Multiple Multiple Multiple/Continuous Multiple	II III III II

Table 2-5. (Continued)

State Class: Environment

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Techniques	7 Expected Selection Range	8 Probable Control Type
Compartment pressure	1. Pressure 2. Pressure flucuation 3. Rate of change of pressure	1. Temperature change 2. Leakage	Pressure within operational range	Requirements for: 1) Heat transfer medium 2) Lubrication (gas bearing, etc.)	1. Replenish gas 2. Bleed gas 3. Select heater setting	Multiple Multiple Binary	II II II
Propellant tank pressure	↓	1. Temp. change a) Heater setting b) Power source variations c) Heat transfer from other systems d) Solar shielding e) S/C position 2. Change in pressurant quantity a) Usage b) Leakage	Pressure within operational range	1. Vapor pressure of propellants 2. Operational requirements of thrustors	1. Select heater setting 2. Adjust solar shielding 3. Regulate power source 4. Regulate heating from other systems 5. Reposition S/C 6. Bleed propellant	Binary Binary/Multiple Multiple Multiple Multiple/Continuous Binary	I II II III III II

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Table 2-6. Functional Requirements for Controlling Position (1.3.2)

State Class: Position

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Techniques	7 Expected Selection Range	8 Probable Control Type
Antennae (planar array)	1. Azimuth 2. Elevation	1. Thermal deflection of structure 2. motion of ground a) Settling b) Quakes 3. Motion of S/C a) in orbit b) on ground 4. Relative motion due to celestial kinematics 5. Structural interference	Alignment of antennae with receiving site	Relative orientation between S/C and receiving site(s) a) Ideal values b) Allowable range	1. Modify azimuth 2. Modify elevation 3. Reposition S/C	Multiple/Continuous Multiple/Continuous Multiple/Continuous	II II III
TV cameras	1. Azimuth 2. Elevation	1. Ground motion a) Settling b) Quake 2. Motion of S/C a) in orbit b) on ground 3. Structural interference	Target available within TV field of view	Relative orientation between S/C and target(s)	1. Modify azimuth 2. Modify elevation 3. Reposition S/C	Multiple Multiple Multiple/Continuous	II II III
Solar panel (solar array)	1. Azimuth 2. Elevation	1. Ground motions a) Settling b) Quakes 2. Motion of S/C a) in orbit b) on ground 3. Relative motion due to celestial kinematics 4. Structural interference	Alignment of panel with sun	Relative orientation between S/C and sun a) Ideal values b) Allowable range	1. Modify azimuth 2. Modify elevation 3. Reposition S/C	Multiple/Continuous Multiple/Continuous Multiple/Continuous	II II III
Solar shielding	Position	Solar angle	Solar shield positioned to intercept solar radiation to required extent	1. Temp. ranges of system components 2. Tankage pressures 3. Radiation flux	Modify solar shield position	Binary/Multiple	II
Experiment Configuring	One to six geometric degrees of freedom associated with hardware, i.e. azimuth elevation range rotation open closed, etc.	1. Thermal influence a) Deflection b) Driving gain 2. Motion of S/C a) Orbital b) On ground 3. Motion of Ground a) Settling b) Quakes	Experimental equipment suitably configured	Experiment support requirements a) Relocating sensors b) Preparing area for tests c) Configuring subsystems	Exercise appropriate degrees of freedom a) <3 degrees of freedom b) 3 degrees of freedom	Multiple/Continuous	 II III

Table 2-7. Functional Requirements for Controlling Location (1.3.3)

State Class: Location

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Techniques	7 Expected Selection Range	8 Probable Control Type
Trajectory a) mid-course b) terminal	6 elements to define trajectory	1. Thrust errors 2. Vernier errors 3. Timing errors	Correct trajectory	1. Nature of mission a) Landing b) Orbital c) By-pass 2. Allowable errors	Operate appropriate thrustors a) Magnitude b) Direction c) Duration	Multiple/Continuous	II
c) orbital	1. 6 elements to define orbit 2. Attitude	1. Orbit injection errors 2. Environmental interaction a) Gravity gradient b) Magnetic field c) Solar pressure	1. Correct orbit a) Plane b) Altitude c) Eccentricity d) Phasing 2. Correct attitude	Mission requirements a) Station keeping b) Planetary observation c) Celestial observation d) Environmental measurements	Operate appropriate thrustors a) Magnitude b) Direction c) Duration	Multiple/Continuous	II
Locomotion (Local position)	1. Position 2. Velocity 3. Attitude	1. Mission requirements a) Experimental design b) Quantity of data collected at given point c) Quality of data collected at given point d) Rate of data collection e) Rate of consumption of consumable resources 2. Ground features a) Mechanical properties b) Geometric properties	Optimum location for the collection of desired data	Mission requirements a) Exper. design b) Priority of individual experiments c) Data collected d) Quality of data collected e) Status of S/V resources	Operate driving elements	Multiple/Continuous	III
				Ground features a) Obstructions/hazards b) Degree of uncertainty in locating obstructions/hazards	Operate steering Note: The proper path for any point on the profile is dependent on both the factors affecting the input state (3rd col.) and the required state (5th col.). Thus, there is an almost endless combination of direction commands possible.	Multiple/Continuous	III

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Table 2-8. Functional Requirements for Controlling Auxiliary Power (Part of 1.3.6)

State Class: Auxiliary Power

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Means	7 Expected Selection Range	8 Probable Control Type
Operating power for: A. Sensors (pick-ups) 1. Scientific a) analog b) digital 2. Engineering a) analog b) digital B. Instrumentations* 1. Scientific a) analog b) digital 2. Engineering a) analog b) digital C. Information Transfer 1. Receiving 2. Decoding 3. Processing 4. Storing 5. Transmitting D. Environment Control 1. Heaters a. Sensors b. Instrumentation c. Resources E. Configuration Control 1. Solar panel drive 2. Antenna drive 3. Exp. positioning mechanism 4. Temperature Regulator F. Path Control 1. Attitude control 2. Position control 3. Velocity control	1. Number of loads and power required 2. Power drain (energy output) 3. Storage capacity 4. Power input rate (energy input) 5. Storage state (available stored energy) ↓	1. Charge State of Storage batteries 2. Change in power consumption a) resistance change 1) electrical 2) physical b) Degradation of power consuming equipment 3. Battery temperature 4. Random degradations of power control equipment 5. Relative position of solar energy collector and Sun	1. Unregulated Voltage is: a)____vdc, ± ____vdc b)____vac, ± ____vac ____cps, ± ____cps 2. Regulated Voltage is: a)____vdc, ± ____vdc b)____vac, ± ____vac ____cps, ± ____cps 3. Regulated Current is: ____ma, ± ____ma 4. Ripple≤ ____mv	1. Energy source operational parameters: a) solar collector position b) fuel cell gas pressure	1. Adjust energy source a) position solar collector toward sun b) increase/decrease gas pressure	See analysis of position state Multiple/ Continuous	II
				2. Allowable power consumption a) Magnitude b) Tolerance c) Total	2. Turn off non-essential equipment power - OR - Turn on additional batteries/power source	Binary/Multiple Binary/Multiple	II II
				3. Battery temperature	3. Control battery temperature	See analysis of temperature state	
				4. Availability of back-up power control equipment	4. Select available equivalent power control equipment - OR - Adjust power loads to effect approximation of required state - OR - No correction possible	Binary/Multiple Binary/Multiple/ Continuous	II
				5. Solar angle relative to local zenith	5. Adjust solar array to position where solar angle ≥ ____°. - OR - Discontinue non-essential activities until solar angle is again ≥ ____°.		II
				6. Requirement to execute action needing power	6. Execute desired action by: a) reducing non-critical load power consumption b) Increasing power output capability by using reserve power source		II

* Amplifiers, electronic auxilaries, etc.

Table 2-9. Functional Requirements for Controlling Information Transfer (1.3.4 & 1.3.5)

State Class: Information Signals

1 State Subclass	2 Parameter	3 Factors that Cause State Variations	4 Required State	5 Information Required to Determine Current State	6 Correction Techniques	7 Expected Selection Range	8 Probable Control Type
1. Experiment Information Signals on: a) Picture b) Sensor 2. Engineering Information Signals on: a) Environment b) Position c) Location d) Power e) Command Signals (for Verification)	The quality of telemetry, picture, or command signals can be expressed in terms of the following: a) data rate or bandwidth b) error rate or S/N ratio c) changes in data rate or bandwidth d) changes in error rate or S/N ratio.	1. Commutation mode shift 2. Signal conditioning mode shift 3. Transmission mode shift 4. Antenna mode shift 5. Operating power input to sensor and associated electronics is out of tolerance 6. Degradation of sensor or associated electronics including interconnections; i.e., reliability 7. Thermal environment exceeds limits 8. Spurious commands	An RF signal with ___ watts output power, modulated by ___ informations with accuracy > ___, and radiated toward Earth with a gain of ___ db or stored within spacecraft	1. Present selections of: a) Sensor(s) b) Sensor gain(s) c) Commutation Mode d) Modulation Mode e) Transmitter Power Level f) Antenna	1. Selection of proper: a) Sensor(s) b) Sensor gain(s) c) Commutation Mode d) Modulation Mode e) Transmitter Power Level f) Antenna	 Multiple Multiple Multiple Multiple Multiple Multiple	 II II II II II II
				2. Position of Antenna relative to Earth	2. Reposition Antenna	Multiple/Continuous	II
				3. Operating power input to information transfer equipment	3. Adjust power input by a) Reposition solar array b) Select other power source	 See analysis of position state See analysis of power state	
				4. Number of separate signals requiring (near) simultaneous processing	4. Same as 1c through 1f, and/or 5		
				5. Obscuration of S/C relative to Earth DSIF	5. Store signals until radio contact is reestablished a) Store data b) Readout stored data	 Binary Binary	 I I
				6. Degradation of a) Processor b) Transmitter c) Antenna	6. Select different a) Processor b) Transmitter c) Antenna	 Binary Binary Binary	 II II II

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Determining or measuring the status of a given state parameter is, in many cases, not a straightforward task. Frequently, indirect measures have to be obtained to estimate the status of a state parameter at a given time. These measures, or information required to assess the state of concern, are listed in column 5.

If a state is out-of-tolerance or is drifting out-of-tolerance, steps must be taken to regain the desired state. The specific corrective action required depends on the design of the spacecraft means and the condition of the state (and other states that impact it), and cannot be itemized in this table. Only the general technique to correct the undesirable or adverse state is listed in column 6, with the range of alternate actions for each technique listed in column 7. The last column (column 8) shows the probable control type. The expected selection range in column 7 is the number of discrete selections that are expected to be required of the mechanism or component performing the function. For example, binary indicates that there are only two states that the component controlling the state can be in, such as ON or OFF. Multiple indicates that several levels or degrees of a state are expected to be required, e.g., signal amplification may be high, medium, low, and off. If the number of levels, positions, or steps is very high, e.g., position of a movable antenna, the selection range is listed as continuous.

The entries in column 7 are based primarily on judgments by the analysts. These judgments, however, are based on considerations of the types of equipment various JPL representatives and documents indicate could be candidate means for the spacecraft systems. The entries in column 6 are also judgmental, but less so than column 7. The alternative corrective actions are also dependent upon the specific spacecraft design. However, a reasonable list of alternate corrective actions are identified by operating at the techniques level, rather than trying to define specific actions. Most of the techniques were identified by logical derivation from the general characteristics of the candidate equipment classes. However, some of the techniques identified are based solely on judgments by the analysts on what appeared to be reasonable techniques.

Column 8 was provided solely as a means of judging the general complexity of the controls required. The entries cannot be defended since the specific design of the spacecraft will, in many cases, alter the control type. However, the judgments are useful for providing some insight into the similarity of control complexities for various types of state parameters. The three control types are defined below:

Control Type I

Control Type I indicates that a relatively simple or easily determinable control action is required. This action is assumed to be predictable, and can be programmed or automated within the ground-control station. The action may be executed on the basis of monitoring and detection alone, i.e., no decision making is required. These assumptions are based on the following definition of Control Type I.

1. The initiating state, A, is predictable in form and time.
2. There is only one desired state, B, for each state A.
3. The process of going from state A to state B is fixed.

Therefore, all courses of action of Control Type I are predictable on the basis of either a time- or event-based state. That is, there is a one-to-one relation between the control sequence and the initiating state. This is primarily a detection problem, since a desired state B is dependent upon either the existence of state A or of time.

Control Type II

Control Type II indicates a requirement for decision making as well as detection. The required decisions are assumed to be relatively simple. They do not lend themselves to complete automation since the determination of when a situation exists requiring action may be a judgmental process. The required actions, once it has been determined there is need for control, are assumed to be definitive and can be preprogrammed for execution.

These assumptions are based on the following definition of Control Type II.

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1. The initiation state, A, is predictable in form but not in time.

2. The specific desired state (B_i; $i = 1 \ldots x$) given state A, is a function of the time of occurrence of state A. Therefore, state B is a function of state A and time.

3. The process of going from state A to each state B_i is fixed; that is, a fixed sequence is followed within the spacecraft.

These conditions indicate that detection and some decision making are required. In addition, Control Type II requires that the alternate states, together with the selection criteria, be presented. A priori programming may be used, but an interruption and revision capability must be provided. This technique lends itself to automation, but it is expected that human intervention is required, particularly when the criteria for selection between alternate courses of action cannot be quantified.

Control Type III

Control Type III involves those control actions requiring decision making and execution in real time. This control type requires judgment in detection, assessment, and in determining an appropriate course of action. It is assumed that the great number of alternate courses of action may, in most cases, render preprogrammed control ineffective. These conclusions are based upon the following definition of Control Type III.

1. The initiating state, A, is predictable in gross form but not in time.

2. The specific desired state (B_i; $i = 1 \ldots x$), given state A, is a function of data, location, time, and resource states.

3. The process of going from state A to each state B_i is not fixed.

The preceding conditions define the real-time control requirements for effecting state changes. Multiple contingencies are expected which will limit the number of stored sequences and the length of each stored sequence. These conditions indicate the requirement for command sequence formulation in real time within the RCS. This control type requires the presentation of the parameters making up the state to be detected, since it is predictable in form only. Also criteria to determine state B, as well as guides to reach that state, must be available. Therefore, man cannot be excluded from the control loop in this category of commands.

A brief summary of the performance responsibilities of the six major functions of a generic spacecraft system is presented in table 2-10.

Table 2-10. General Responsibilities of Spacecraft Functions.

Function No.	Title	Type of Performances	Responsibility
1.3.1	Control Environment	Sensing Regulation	Those performances concerned with the maintenance of temperature, pressure, and humidity of the space vehicle and associated subassemblies within the required operational range.
1.3.2	Control Position	Support/ Position Separation Shielding Maintenance	Those performances concerned with the repositioning or deployment of mechanical assemblies, i.e., solar collectors, directional antennas, and experimental mechanisms.
1.3.3	Control Location	Space Propulsion Guidance/ Navigation Attitude Control Surface Locomotion Guidance/ Navigation	Those performances concerned with the relocation or orbital maintenance of the space vehicle.
1.3.4/5	Transfer Information	Reception Conditioning Storage Transmission	Those performances concerned with the reception, processing, and transmission of information.
1.3.6A	Collect Scientific (& Engineering) Data	Detection Measurement	Those performances or changes required of a sensor such as turn-on, calibration, adjust output signal by amplification, and turn-off which are considered to be specific to the sensor.
1.3.6B	Control Auxiliary Power	Energy Collection Energy Storage Power Conditioning Power Distribution	Those performances concerned with the provisioning of electrical power at a satisfactory operational level.

REMOTE CONTROL STATION REQUIREMENTS

The overall control system is defined as that set of means required to support the spacecraft during its operational lifetime. In this project, this system encompasses the DSIF, GCS, and SFOF. The remote control station is considered as a segment of the SFOF.

The responsibility of the remote control station is to furnish control signals to a class of spacecraft. These spacecraft have lunar and near-planet destinations. The MARINER, SURVEYOR, VOYAGER, and ORBITER vehicles are typical of this class. Although control requirements exist throughout the mission profile, the greatest stress on the control station is during the on-station portion of the mission. The requirements originating from this part of the overall mission are then the primary concern of this study.

Specific functions must be accomplished within the spacecraft to achieve the mission objectives. Control[1] is required for this accomplishment. This is the responsibility of the RCS. The RCS output, in the form of commands, must be furnished to the spacecraft in response to the data-collection objectives. The control requirements originate with the need for determining: (1) existing spacecraft state; (2) desired state as prescribed by data-collection objectives; and (3) required spacecraft functions to achieve the desired state. The specific control requirements for a generic spacecraft are expressed in terms of the data-collection objectives; e.g.,

(1) Type of data to be collected,
(2) Quality and quantity of data,
(3) Duration of data-collection process,
(4) Mission profile, i.e., destination and path to the destination,

and the spacecraft functions required to implement these objectives.

The capability to control a state is a function of: (1) the tolerance within which that state must be maintained; (2) the rate of change of that state; and (3) the stability of the rate. Depending upon these variables alone, the control of the state in question can be allocated to: (1) the spacecraft, i.e., the response requirements exceed the ground-control capability; (2) ground-based, automated-processing and decision-making equipment; and (3) ground-based, manual decision making and control. To facilitate the allocation of ground-based means required to effect various state changes, a classification of the spacecraft state changes was derived by inquiring into the ability of the ground-based control system to predict future state changes necessary to accomplish the mission objectives. These classes were defined as control types I, II, and III. Control type I is predictable on the basis of either a time- or event-based state, thereby relegating the problem primarily to one of detecting the initiating state. This type of control is highly amenable to automation.

Control type II is similar to type I except the initiation state is predictable in form only (i.e., not in time), and the corrective action is a function of the time of occurrence of the initiating state. This type of control is also amenable to automation but not as easily as I, since more control alternatives must be considered.

Control type III is the most complex in that the initiating state can only be predicted in gross form and the corrective action cannot be specified in advance. This type of control cannot be automated and generally requires a skilled and experienced decision maker.

COMMAND/CONTROL REQUIREMENTS

The first step in defining the specific requirements for the RCS was to synthesize the spacecraft requirements information presented in the previous section and present them in terms specific to the RCS. The results of this synthesis are presented in tables 2-11 through 2-17 in the form of command/control requirements for the RCS.

The command/control requirements were obtained primarily from the spacecraft functional requirements tables (tables 2-5 through 2-9). Although some modifications were made to orient the requirements to the RCS, the two sets of tables are quite similar. The differences occur primarily from limiting actions and information needs to the RCS situation. In addition, television control is treated as a separate set of command/control requirements whereas it was treated as part of scientific data collection previously. The data were obtained by synthesizing various JPL documents describing the requirements for and use of television in scientific data collection.

Despite the details provided, the command/control requirements presented in tables 2-11 through 2-17 represent the top-level requirements for the RCS. They are the governing set of requirements for all subsequent analysis/design endeavors. They provide the basic set of inputs and outputs requirements for the RCS. The outputs are defined by the action necessary column (column 5). The criteria for the action are defined in columns 1, 2, and 3. The conditions which determine when the control actions are required are defined in column 4. The inputs, or information required, to guide the controlling actions are provided in column 6. Column 7 indicates the relative complexity of the controls.

[1] Control means assessing the vehicle or subsystem status, determining a course of action, and implementing that desire.

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Table 2-11. RCS Command/Control Requirements

State Class: Data Collection

Type of Data (1)	State Parameters (2)	Required State* (3)	Factors That May Cause Requirement for State Change (4)	Action Necessary to Achieve Required State (5)	Information Required to Effect State Change (6)	Relative Complexity of Control Process & Probable Control Type (7)
Properties of Force Fields 1) Gravity 2) Magnetic 3) Electrostatic	Potential and polarity vs. time in cm/sec^2, gauss, statvolts, etc.	Location state ____	Completion of experiment objectives (all or part) Reallocation of priorities Occurrence of significant event ** Thermal variations in excess of design limits	Locate sensor via location control (See Table 2–14)	Data collection requirements via mission plan and analysis of prior data.	See Table 2–14
Properties of Radiation 1) Electro-magnetic 2) Charged particle	Energy density, energy distribution, intensity flucuations, velocity distribution, spatial orientation, etc.	Position state ____	Same as above	Position sensor via position control (See Table 2–13)	Existing sensor location and position.	See Table 2–13
Properties of Matter 1) Chemical	composition structure distribution	Temperature within ____ ^oF to ____ ^oF	Completion of experiment objectives Solar angle Internal energy generation Power limitations	Maintain temp. via environmental control (See Table 2–17)	Sensor temp. and limits	See Table 2–17
2) Electrical	conductivity magnetivity emissivity	Amplifier gain set to ____	Degradation of sensor or associated electronics Occurrence of significant event	Select gain setting of ____	Sensor gain setting	b*** I****
3) Mechanical	density strength elasticity					
4) Geometrical	size shape distribution	Sensor and associated electronics calibrated to ____	Completion of experiment objectives (in part) Degradation of sensor and/or associated electronics Occurrence of significant event including motion	Calibrate sensor via routine ____	Sensor calibration data	a I
5) Thermal	conductivity absorptivity emissivity					

* The required sensor state is a function of the original mission objectives modified as a result of the interpretation of previously collected data and the resources available to accomplish desired objectives.

** Natural or man-made phenomena.

*** See assessment complexity definition

**** See control type definition

Table 2—11. RCS Command/Control Requirements (continued)

State Class: Data Collection

Type of Data [1]	State Parameters [2]	Required State* [3]	Factors That May Cause Requirement for State Change [4]	Action Necessary to Achieve Required State [5]	Information Required to Effect State Change [6]	Relative Complexity of Control Process & Probable Control Type [7]
		Sensor activated/deactivated for ___units of time or ___data points, and sensor must be on continuously for__ units of time w/o interruption of >___units of time.	Completion of sensor objectives (all or part) Occurrence of significant event Reallocation of priorities Power limitations Telecommunications Limitations	Turn sensor and associated electroics on or off.	Data from sensor in form compatible to: 1) Determine quality of data. 2) Determine % completion of objectives within___time units of event.	C I
					Data from other operations (including time of occurrence) necessary for cross correlation as requested.	

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Table 2-12. RCS Command/Control Requirements

State Class: Image Collection

Type of Data (1)	State Parameters (2)	Required State (3)	Factors That May Cause Requirement for State Change (4)	Action Necessary to Achieve Required State (5)	Information Required to Effect State Change (6)	Relative Complexity of Control Process and Probable Control Type (7)
Television	Azimuth	Azimuth = ______	Data requirements* S/C attitude	Select azimuth drive direction Select azimuth drive rate Select azimuth drive duration	S/C attitude Camera azimuth ∡ Required azimuth ∡	b II
	Elevation	Elevation = ______	Data requirements* S/C attitude	Select elevation drive direction Select elevation drive rate Select elevation drive duration	S/C attitude Camera elevation ∡ Required elevation ∡	b II
	Focal Length	Focal length ____mm, or field of view = ____.	Data requirements*	Select focal length	Camera focal length Required focal length	b I
	Focus	Focus = __________	Distance to target	Select focus	Current camera focus Reference target Distance to target	b II
	Filters	Filter number ____, 1 of _____.	Data requirements* Solar angle	Select filters	Colorimetric data requirement Current filter setting	a I
	Shutter Speed	Shutter speed = _____, 1 of _____.	Illumination Data requirements*	Select shutter speed	Aperature setting Illumination Required depth of view	b II
	Aperature	Aperature opening = _____, 1 of _____.	Illumination Data requirements*	Select aperature setting	Shutter speed Illumination Required depth of view	b II
	Temperature	Temperature within _____°F and _____°F.	Operational duty cycle Solar angle Other components in operation	Alter operational rate Shield/expose TV elements to incident solar radiation Turn heater on/off (See Table 2-17)	Temperature Solar angle S/C attitude Antenna/solar array position Available power Thermal loads in use	b II
	Camera Power Mode	Television picture of ________ lines/inch.	Antenna degradation Transmitter degradation Power availability	Switch antenna Switch transmitter Switch camera mode to _____lines/inch (See Table 2-16)	Telecommunication availability Power availability TV picture quality	b II

* The required (or desired) states and/or state changes will be derived from mission plan objectives, other experiment objectives requiring TV support, and interpretation/analysis of previously collected images.

Table 2-13. RCS Command/Control Requirements

State Class: Position

Type of Positioning Elements Requiring Control (1)	State Parameters (2)	Required State (3)	Factors That May Cause Requirement for State Change (4)	Action Necessary to Achieve Required State (5)	Information Required to Effect State Change (6)	Relative Complexity of Control Process and Probable Control Type
Antenna (planar array)	Azimuth Elevation	Alignment of antenna with receiving station within ± ___ °.	Planet rotation S/C attitude change S/C motion Transmitter power level change	Change azimuth ∡ Change elevation ∡ Alter S/C attitude	Antenna pointing ∡ Ephemeral data Transmitter mode Resource availability 1) Power 2) Telecommunications S/C attitude	a II
Solar Array	Azimuth Elevation	Alignment of solar array in accordance with desired charge rate.	Change in battery state Planet rotation S/C attitude Requirement to shade S/C	Change azimuth ∡ Change elevation ∡ Alter S/C attitude	Solar array pointing ∡ Ephemeral data Charge rate Battery state Thermal properties of S/C Resource availability 1) Power 2) Telecommunications S/C attitude	a II
Experiment Support Mechanism Deployment (irreversible)	Position; i.e., retracted, position 1, position 2, etc. in terms of degrees of deployment.	Position ___	Data requirements	Actuate next position (sequential)	Data requirements in terms of when to change position Existing position Resource availability 1) Power 2) Telecommunications	a I
Positioning (reversible)	Position 1) Azimuth 2) Elevation 3) Extension 4) Rate of motion 5) Direction of motion	Azimuth ___ Elevation ___ Extension ___	Data requirements Surface topography Changes in S/C attitude	Move in elevation Move in azimuth Move in extension Select rate Select direction of motion	Data requirements in terms of target position Existing position Surface topography within positioning sector Resource availability 1) Power 2) Telecommunications S/C attitude	c III

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Table 2 —14. RCS Command/Control Requirements

State Class: Location

Type of Location Mechanism Requiring 1	State Parameters 2	Required State* 3	Factors That May Cause Requirement for State Change 4	Action Necessary to Achieve Required State 5	Information Required to Effect State Change 6	Relative Complexity of Control Process & Probable Control Type 7
Mobile Surface Vehicle	Distance, and Direction or Coordinates with respect to selected reference.	Location along azimuth___°at distance___feet, or at coordinates ___and___with respect to current location. Attitude not to exceed___°in pitch and___° in roll. Velocity not to exceed___fps. Power consumption not to exceed ____watts. Temperature to be maintained within___°F and ___°F.	Data requirements expressed in location terms. Unfavorable terrain features at existing location 1) Shifting attitude 2) Sinking Adverse thermal state requiring either shaded or non-shaded location. Transmission obscuration with receiver station (assuming capability to receive at S/C).	Select steering angle Select step** size or motive rate Steer antenna (See Table 2-13) Steer solar array (if any) (See Table 2-13) Operate camera (See Table 2-15) Control temperature (See Table 2-17) Control camera parameters (See Table 2-15)	S/C Attitude S/C Steering angle S/C Heading Power availability Vehicle Status 1) Temperature 2) Operational characteristics Target location Terrain Characteristics 1) Slope 2. Protuberances 3) Depressions 4) Trafficability (surface hardness) Telecommunications availability	c III

*Required states and/or state changes derived from interpretation/analysis of experimental data, video images on topography of surface, and desired mission objectives expressed by mission plan.

**Greatest distance that can be traversed without stop for reassessment.

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Table 2-15. RCS Command/Control Requirements

State Class: Auxiliary Power

Type of Power Consuming Components (1)	State Parameters (2)	Required State (3)	Factors That May Cause Requirement for State Change (4)	Action Necessary to Achieve Required State (5)	Information Required to Effect State Change (6)	Relative Complexity of Control Process (7)
Data Sensors Instrumentations* Information Transfer Environmental Control Position Control Location Control	Power storage capacity Power input rate Power output rate 1) Number of loads 2) Power/load Power availability	Power input rate < ______.	Solar angle 1) S/C motion 2) Planet rotation Solar array degradation Temperature variation	Position solar array	Solar array pointing ∡s Charging rate Temperature Power availability S/C attitude	b II
		Power output rate < ______.	Loads consuming power Temperature Equipment degradation	Regulate loads consuming power Turn heaters on/off	Experiment requirements Temperature Storage depletion rates Power availability	b II
		Power storage > ______.	Temperature of store Charge/discharge rates No. of charge/discharge cycles Day/night cycle	Turn heaters on/off Regulate discharge load Regulate charge rate	Temperature Store voltage Ephemeral data Power availability Charge/dischg. cycles	a II

*Amplifiers, electronic auxiliaries, etc.

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Table 2-16. RCS Command/Control Requirements

State Class: Information Transfer

Information Signal Type (1)	State Parameters (2)	Required State (3)	Factors That May Cause Requirement for State Change (4)	Action Necessary to Achieve Required State (5)	Information Required to Effect State Change (6)	Relative Complexity of Control Process (7)
Picture Telemetry Retransmitted Command	The quality of telemetry, picture, or command signals can be expressed in terms of the following: data rate or bandwidth error rate or S/N ratio changes in data rate or bandwidth changes in error rate or S/N ratio.	Xmitter, 1 of ____	Xmitter degradation	Select Xmitter ____	Xmitter selection Signal quality	a - II
		Xmitter Mode, 1 of ____	Power degradation Temperature variation Data requirements	Select Xmitter Mode ____	Data requirements Power availability Temperature Xmitter mode selection	a - II
		Antenna Mode, 1 of ____	Antenna degradation S/C attitude Power state Data requirements	Select Antenna Mode, 1 of ____	Antenna selection Signal quality Power state S/C attitude	a - II
		Commutation Mode, 1 of ____	Data requirements	Select Commutation Mode, 1 of ____	Data requirements	a - II
		Temperature Within ____ °F ± ____ °F	Temperature rise 1) Excessive power usage 2) Solar angle Temperature fall	Reduce power level Shade from sun Turn heater on/off	Temperature Power consumption Power availability	b - II
		Antenna aligned within ____ ° of Earth-Spacecraft line	S/C motion Earth rotation Planet/Moon rotation	Reposition antenna	Antenna pointing ∡s S/C attitude Ephemeral data Power availability	b - II
		Receiver, 1 of ____	Receiver degradation	Select receiver ____	Knowledge that command was not received or in error	a - II
		Store/Readout data at spacecraft	Obscuration of S/C relative to earth Power degradation	Select store mode Select readout mode	Power state Ephemeral data Absence of signals	a - II

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Table 2-17. RCS Command/Control Requirements

State Class: Environment Control

Type of Component Requiring Environmental Control (Temperature) [1]	State Parameters [2]	Required State* [3]	Factors That May Cause Requirement for State Change [4]	Action Necessary to Achieve Required State [5]	Information Required to Effect State Change [6]	Relative Complexity of Control Process [7]
Sensors	Temperature Rate of change of temperature	Temp. within __ °F to __ °F (for operation) Temp. within __ °F to __ °F (for survival) Temp. change not to exceed ___ °F/hr	Solar angle Change in radiative transfer rate S/C attitude	Turn heaters on/off Turn sensors on/off Shade by positioning mechanism Change S/C attitude	S/C attitude Ephemeral data Temperature Heater state Power availability	b II
Electronics (Instrumentations)	Temperature Rate of change of temperature	Temperature within __ °F to __ °F	Solar angle Variation in thermal characteristics Power consuming loads operating	Turn heaters on/off Turn power consuming loads on/off Shade by 1) S/C attitude 2) Solar array Activate/deactivate heat blocks	S/C attitude Ephemeral data Temperature Loads in use Heater states Heat block states Power availability	b II
Battery	Temperature Rate of change of temperature	Temperature within __ °F to __ °F	Charge state Charge/discharge rate	Alter charge rate Alter discharge rate	Charge/discharge rate Temperature Power availability	b II
Structure	Temperature Rate of change of temperature	Temperature difference between __ component and __ component to be less than __ °F	Solar angle S/C attitude	Turn heaters on/off Activate/deactivate heat blocks Change S/C attitude	Temperature S/C attitude Ephemeral data Heat rejection characteristics Power availability	b II

*Required temperature states and rate of change of those states expressed for operation of data collection sensors and supportive subsystems as well as their survival temperature limits.

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The I, II, and III codes in column 7 are the control type codes used in tables 2-5 through 2-9. The letter codes are specific to tables 2-11 through 2-17 and were used merely to "capture" judgments relative to complexity obtained while analyzing the subsets of each function. These judgments proved to be of some use in later efforts for allocating means, but the contribution to design conceptualization cannot be quantified. They are included merely to show the judgments made during the analysis since these judgments had some unknown effect on design conceptualization. The codes are described below.

Complexity a. —A simple task of correlating a quantitative value received by telemetry data or switch position with a specific spacecraft state. Little or no interpretation is required since there is a one-to-one correspondence between the existing state and the cue. An example might be telemetry data from a microswitch indicating that a mechanical element is against a stop. Assessment of this order of complexity can be easily programmed for computers.

Complexity b. —A moderate amount of interpretation is required to establish or estimate the true state of the spacecraft function or subsystem of concern. It is anticipated that this order of assessment complexity will require the attention of personnel to a limited extent even though computer programs could be written to correlate telemetry data with an existing state. An example of an assessment function complexity of type b might be to determine that the temperature of a particular electronic compartment was due to solar impingement instead of an overloaded electronic component.

Complexity c. —The most severe assessment loads occur in this category. Analysis, interpretation, and judgment of such an order to require man comprise this order of complexity. Assessment of the spacecraft environment by photoanalysis is an example of assessment type c. Situations where multiple contingencies exist will probably require assessment of this complexity.

CONSTRAINTS AND DELIMITATIONS OF RCS

SFOF Characteristics (See the JPL SFOF Design Book, Vol. I, October 1963.)

Since the RCS is to be situated within the SFOF, certain characteristics of the SFOF will have a constraining effect on the design of the RCS. These characteristics are discussed briefly in this section.

The primary function of the SFOF is to provide a relatively mission-independent capability for data processing, data analysis, information display, communications, and DSIF support.

The SFOF is located at the Jet Propulsion Laboratory. It has been designed to reflect the philosophy that the effective planning for, and execution of a spacecraft mission is best conducted from a centralized facility. The facility currently comprises mission-independent, facility-oriented functions, and mission-dependent, project-oriented functions. The mission-independent functions encompass data processing, communications, facility control, and DSIF control. The requirements for these functions vary relatively little from project to project. Mission-dependent functions that vary in execution (but not in function) are analysis of spacecraft performance, analysis of flight path, and analysis of the television images. The specific requirements of these functions, of course, vary from mission to mission.

It is assumed that the RCS will be responsible for the real-time control commands. Currently, there is no provision for providing a direct link to the DSIF from the RCS (within the SFOF). This could become a severely limiting constraint for real-time control if the lack of a direct link results in a significant time delay in transmitting the necessary commands. The specific allowable delay between the initiating state and the achievement of the required state is not yet known. Considering the fairly large percentage of type III control, the lack of a direct link could place a time stress on relatively complex real-time decision making. This stress can only be alleviated by reducing the time delay between the decision to execute and the ability to do so. This indicates that a direct couple system (RCS to DSIF) would be highly desirable. The necessity for a direct couple system cannot be verified until a quantitative analysis of operating time requirements is conducted.

Table 2-18. Ground Communications System Within the Deep Space Network—July 1965
NOTE: Simultaneous Terminations are Hardware Limited at DSN Communications Center*

STATION	DIRECTION	TELETYPE	VOICE	HIGH-SPEED	LINK CAPABILITIES
Goldstone					
DSIF 11	Outgoing to SFOF	6	7	4	Microwave Carrier Video Channel = 60 cps/ 6 mc
DSIF 12 DSIF 13	Incoming from SFOF	6	7	4	Wideband Data Channel 300 cps/96 kc
NOTE	Backup Facilities Landline	6	2	1	
Australia					
DSIF 41	Outgoing to Adelaide	3	2	1	Teletype = duplex lines
	Incoming from Adelaide	3	1	0	High-Speed = 60/1200 bps line transfer rates
DSIF 42	Outgoing to SFOF	4 6**	1	1	
	Incoming from SFOF	4 6**	1	0	
South Africa					
DSIF 51	Outgoing to SFOF	5	2	1	Teletype = duplex lines
	Incoming from SFOF	5	2	0	High-Speed = 550 bps line transfer rates
Europe					
DSIF 61	Outgoing to SFOF	4	3	0	Teletype = duplex lines
	Incoming from SFOF	4	3	0	High-Speed = 600/1200 bps line transfer rates
Eastern Test Range					
Cape	Outgoing to SFOF	3	2	1	Teletype = duplex lines
DSIF 71	Incoming from SFOF	3	2	1	High-Speed = 600/1200 bps line transfer rates

*Taken from JPL Engr. Planning Document No. 283, September 1965.
**Projected

The SFOF can make available to the project users various displays and devices. These include teletype (TTY) page printers, reperforators, and input keyboards; closed circuit television (CCTV) monitors; data-processing system (DPS) input/output devices; bulk printers; card readers; teleprinters; plotters; analog recorders; and wall-mounted displays (ref. JPL/EPD-283). It appears reasonable to assume that RCS functions will be required to use these means if they can satisfy the requirements for the functions.

Communications Link

The values assumed to be representative of the information links between the spacecraft and the remote control station are also a function of the Ground Communications System (GCS). This system—part of NASCOM—is assumed to have the existing capabilities represented in table 2-18.

Further improvements to the communications system may include:

1. Data transmission rates up to 7200 bps via telephone circuitry;

2. Communications processors with nanosecond access time, 100 k core, etc.;

3. Digitized voice channels on HF radio path;

4. Adaptive HF radio with 50 m sec shifting;

5. Communications via satellite, either NACOM-owned or commercial.

For this study the information exchange between the remote control station and the space vehicle was assumed to consist of three links. Each link is briefly described as follows:

Command Link

The expected range of command capability, expressed in bits per second, is assumed to be from 1 to 200. It is anticipated that 10-100 bps will be common. This is in conformance with the design specifications for command verification equipment to be used at the DSIF, per JPL Spec GMG-50109-DSN-A, 20 October 1964. A command word may consist of nominally 10-20 bits; therefore, the time to transmit a single command may vary from 1/10 to 2 seconds.

Telemetry Link

The received information, spacecraft to Earth, may vary considerably, depending upon the distance from Earth and the telemetry mode selected. The variation may be as high as from 4 bps from a simple planetary space vehicle like MARINER, to 4400 bps for an advanced lunar vehicle such as SURVEYOR. Advanced lunar vehicles are expected to have telemetry rates that permit transmission of all of the required measurements within about 5 seconds. The transmission rate of a planetary vehicle may be a factor of ten slower than that of a lunar vehicle, if the same spacecraft configuration is used.

Picture Link

At lunar distances, the power requirements for the transmission of images does not require long-term image storage. The target of a vidicon will hold the picture for a few seconds so that readout can be accomplished. Thus, at lunar distances, it is assumed that an image may be obtained and transmitted towards the Earth within a few seconds of receipt of the command at the spacecraft. Longer storage times imply longer transmission times. For MARINER, this time amounted to several hours.

Communications Window

Spacecraft on-station functions impose three types of problems relative to ground control. These are concurrency, priority, and viewing. Multiple spacecraft control compounds these problems, since different DSIF may be operated simultaneously or one DSIF may have to be time-shared between spacecraft. Other ground-based resources of the data-collection system may be similarly involved.

In view of the limited time available (i.e., the life cycle of the spacecraft), it might be ideal to collect all scientific data simultaneously. This is not possible, however, because of limited power availability, limited bandwidth to command the spacecraft subsystems and telemeter the resulting information back to the ground, and the need to collect data under a diversity of conditions. This latter requirement necessitates collecting data over a period of time either to achieve the desired environmental conditions or to obtain the necessary sample over a representative time span. Power and bandwidth constraints may be noted in all spacecraft systems. For example, potential interference is noted in the seismic experiment wherein other subsystems which may generate artificial noise may have to be shut down.

Since concurrency is not always possible or desirable, collection of data very likely will be scheduled on a priority basis, assuming certain types of information have more value to the scientific community than others. With this consideration, a hierarchy would be arranged for the meeting of experimental objectives. Although the primary requirement of the spacecraft on-station is the collection of scientific data, it may be necessary to interrupt this function to attend a different functional subsystem that shows indications of degraded performance. An example is the requirement to reorient the solar energy collector because of a decreasing voltage in the auxiliary power subsystem. Generally, these interruptions are concerned either with the degradation of information being collected or the survival of the entire spacecraft.

Viewing problems may result either from the Earth's rotation, the planet's rotation, or the spacecraft's orbit about the planet. In all three cases, the problem is loss of direct communication with the spacecraft for the duration of the problem.

Consequently, the overall problem of scheduling subsystem performances on the basis of priorities or concurrencies will be affected also by the problem of the available view window. Even though a certain performance may have a high priority, it may be necessary to abbreviate that performance because of an impending loss of communications coverage. When the Earth's rotation is responsible, it is not possible to have the spacecraft in direct communications with a primary tracking station (Goldstone). It has been hypothesized that the exclusive experiments require a primary tracking station because of the communications bandwidth between the DSIF and a centralized ground-control station whereas the concurrent functions may be conducted with a narrower bandwidth. The resolution of these constraints will impact the RCS both in terms of operational concepts and available response times.

Telecommunications blackout due to the eclipse of an orbiting vehicle, or planetary rotation, which results in communications shading of a soft-landed spacecraft may cause an additional constraint. Figure 2-13 indicates the constraint of performing exclusive functions A, B, and C to the time limit of direct primary tracking-station coverage. In the generation of these diagrams, it was assumed that all functions require direct control of a tracking station with the exception of concurrent functions B and C. The performance of the exclusive functions is abbreviated in order to complete data collection prior to loss of primary tracking-station coverage, after which time the three concurrent functions are simultaneously performed until the blackout period starts. During the blackout period, concurrent functions B and C are placed in storage. After completion of the blackout time, the information is read out and direct control is again effected.

SPECIFIC RCS QUALITATIVE REQUIREMENTS

As indicated previously, the command/control requirements obtained from synthesizing the spacecraft state-change and functional requirements represent the top-level requirements for the RCS segment of the total system. Requirements at one further level of detail are required to permit

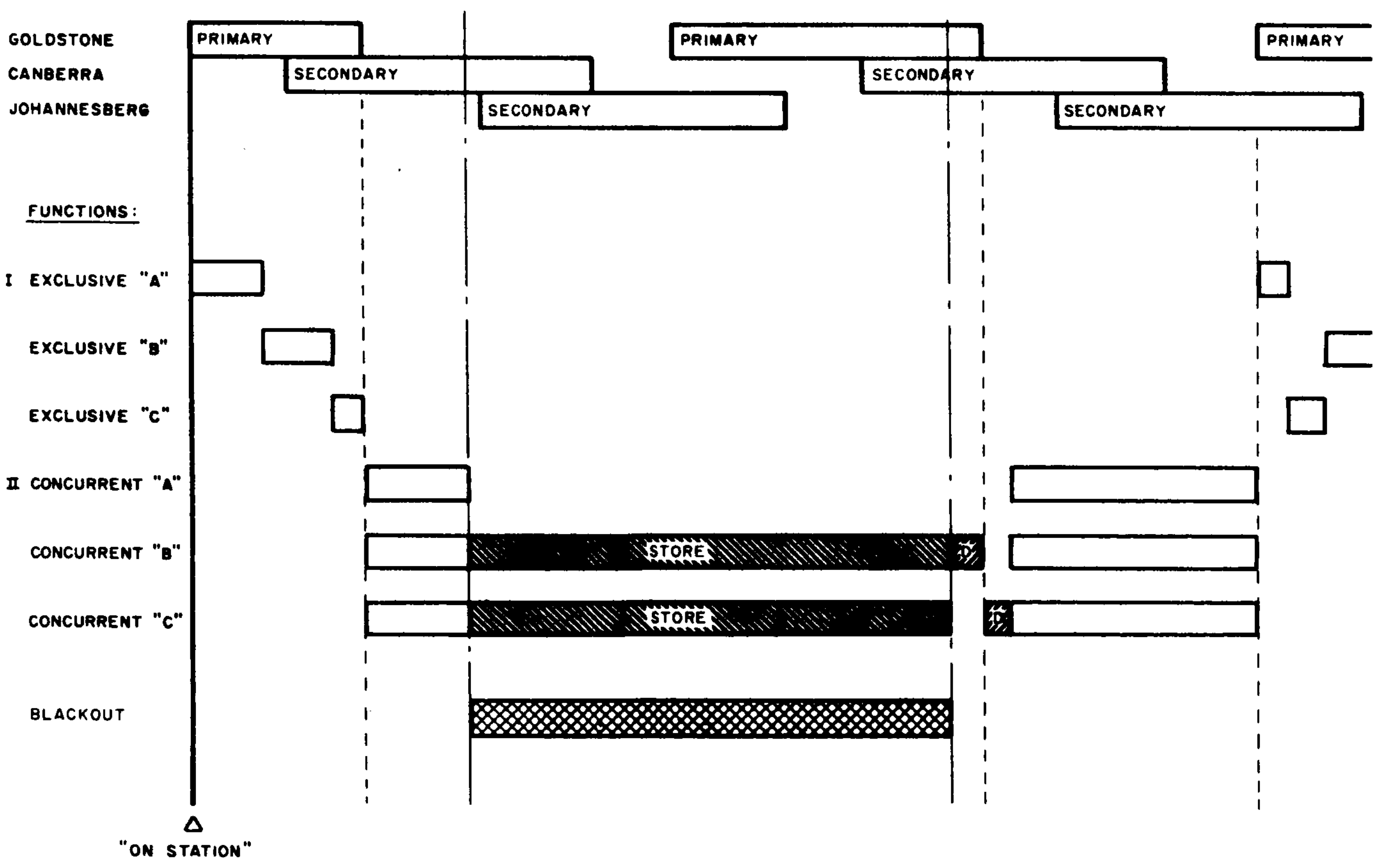

Figure 2-13. Gross time line for spacecraft functions covered by primary and secondary tracking stations, with blackout period.

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development of a conceptual design. The basic functions of the RCS must be partitioned out to allow design considerations to be applied at reasonably manageable levels (ground rule 19). The RCS system is too complex to attempt an approach in toto.

The requirements defined at the functions level are termed "qualitative requirements" since no quantitative value is assigned. The requirements identify the required performance, but do not specify accuracy, quantity, and/or reliability in measurable terms. Quantification is a necessary step but must be preceded by definition of the qualitative requirements.

The state-change analysis technique was used to define the qualitative requirements. To assure systematic analysis and proper scoping of the task, a set of assumptions was developed at the outset, to present the analysis of areas which probably would not be fruitful because of existing approaches or constraints. These assumptions are described below.

Assumptions

1. The control of spacecraft experiments and support functions in real time during the on-station portion of the mission was assumed as a basis for detailed analysis.

2. The implementation of only those functions indicated as principal functions was to be studied in detail. These functions are identified later.

3. Implementation of the specified functions within the RCS would be accomplished by means available within the existing state of technology.

4. All control would be accomplished by means of digital command words. The composition of each word is defined by the telecommunications link.

5. Since all command elements (single command words) can be defined by referring to specific equipment characteristics, their formulation was assumed to be accomplished prior to the mission operational phase and is a function external to the RCS.

6. The storage of single command words was assumed to be a function of the SFOF support complex. The command elements will be addressed by an RCS function for formulation into command sequences for real-time control.

7. When command elements can be ordered into sequences prior to the operational requirement, prior formulation and storage of these sequences was assumed. There are some command sequences which must be structured "on-line"; therefore, formulation of command sequences is required within the RCS.

8. It was assumed that commands would be verified after release from the RCS by means of equipment similar to that planned by JPL telecommunications personnel (JPL Spec GMG-50109). Command verification or reliability requirements are a function of the potential effect of erroneous commands.

9. Although there are times when the RCS must perform computation that will require automatic processing systems, the conversion of the raw data into a form compatible to the RCS (assumed to be of such a nature that it may be displayed or used as computer inputs) is assumed to be accomplished by an RCS external function. The television ground data-handling system (TVGDHS) is such a function.

10. The mechanism to be controlled is assumed to have been designed according to the following philosophy:

a. All actions are to be accomplished in step fashion, either on the basis of time or displacement.

b. No OFF state will be designed to require a state change to avoid mechanism damage, if this is possible; i.e., in the absence of a command, the only loss would be either data or time. There are instances, such as temperature rise or fall, where this condition is unavoidable.

c. Resource expenditures on-board the spacecraft should be minimized during periods of inactivity.

State-Change Requirements

As indicated in the discussion of spacecraft systems, the intermediate state changes provide the boundaries for functions and each pair of state changes defines the requirements for a function.

Thus, the intermediate state-change requirements described in this section are the basic set of requirements for the major functions comprising the RCS. Specifications of performances required within functions are termed "functional requirements." State-change requirements are presented in the form of functional-flow logic diagrams, and functional requirements are presented in both narrative and tabular form.

The intermediate state changes of the RCS were derived by first determining the sequential order in which a set of data (either scientific data or data reflecting spacecraft states) must be changed to "knowledge" states (knowing the actual condition of the spacecraft or scientific data) and eventually to command signals. The references for the input data states are actual states (or a set of conditions) of the spacecraft and the total set of scientific data required. Major contingency states were then identified to define those functions necessary to account for the most likely errors. These latter functions represent the first set of functions assigned for reliability purposes. The set of functions identified by this analysis represents the first functional configuration of the RCS which (1) defines the basic state-change requirements of each function in general terms, and (2) identifies the basic relationship between functions.

In addition to the assumptions discussed in the previous subsection, development of the initial functional configuration of the RCS was based on the one basic concept that command preparation is a function of command type. The three different command types require different orders of state changes in order to achieve rapid response throughout the system. The major differences are discussed below.

Type I

All type I command sequences can be prepared in advance of the mission and stored within the RCS or DSIF. Thus, the use of these commands can be predicted on the basis of an event- or time-based state. They can be retrieved and transmitted to the space vehicle as required.

Type II

The commands that comprise this set can be prepared prior to mission operation if provision is made for sequence revision prior to or during transmission. It is assumed that manual or automatic insertion of commands between fixed sequences will occasionally be required. The requirement for modification can arise from feedback data or from a desire to perform some activity in a different fashion. For example, a programmed panoramic video survey may significantly reduce the overall time of performance even though the sequence may require that an occasional corrective command be inserted into the command string.

Type III

When space vehicle operations, such as movement on the surface, or grasping of objects with an articulative arm, are contemplated, the sequence in which the commands are to be transmitted cannot be predicted in advance. Command sequence fragments may be combined with basic command words to formulate a "continuous" sequence in real time to accomplish the desired objective. It is assumed that manual command-sequence information will be accomplished by actuating controls that "address" command words or sequence fragments. These elements may be transmitted to the spacecraft on an as-retrieved basis, or recorded and transmitted like a type II sequence.

The basic state-change requirements of the RCS (i.e., the functional configuration) are presented in figure 2-14. The basic inputs to this configuration are the data obtained from the spacecraft (interfacing block (s) on the right-hand side of the diagram) with the intervening telemetry data-transfer block (o) shown on the upper-left corner of the diagram. Although the input is shown simply as "decommutated telemetry stream at SFOF," the data are comprised of a complex set of signals represented in column 5 (Information Required to Determine Current State) in tables 2-11 through 2-17. The basic requirement for function 1 (Process Data) is to transform the data into a state acceptable to means of data presentation. In addition, the function will be responsible for transforming command sequence data stored temporarily in the spacecraft into a form which will allow comparison with the command sequences in the form originally transmitted to the spacecraft. It is assumed that this function will also require data on the elapsed time of missions, a computer program

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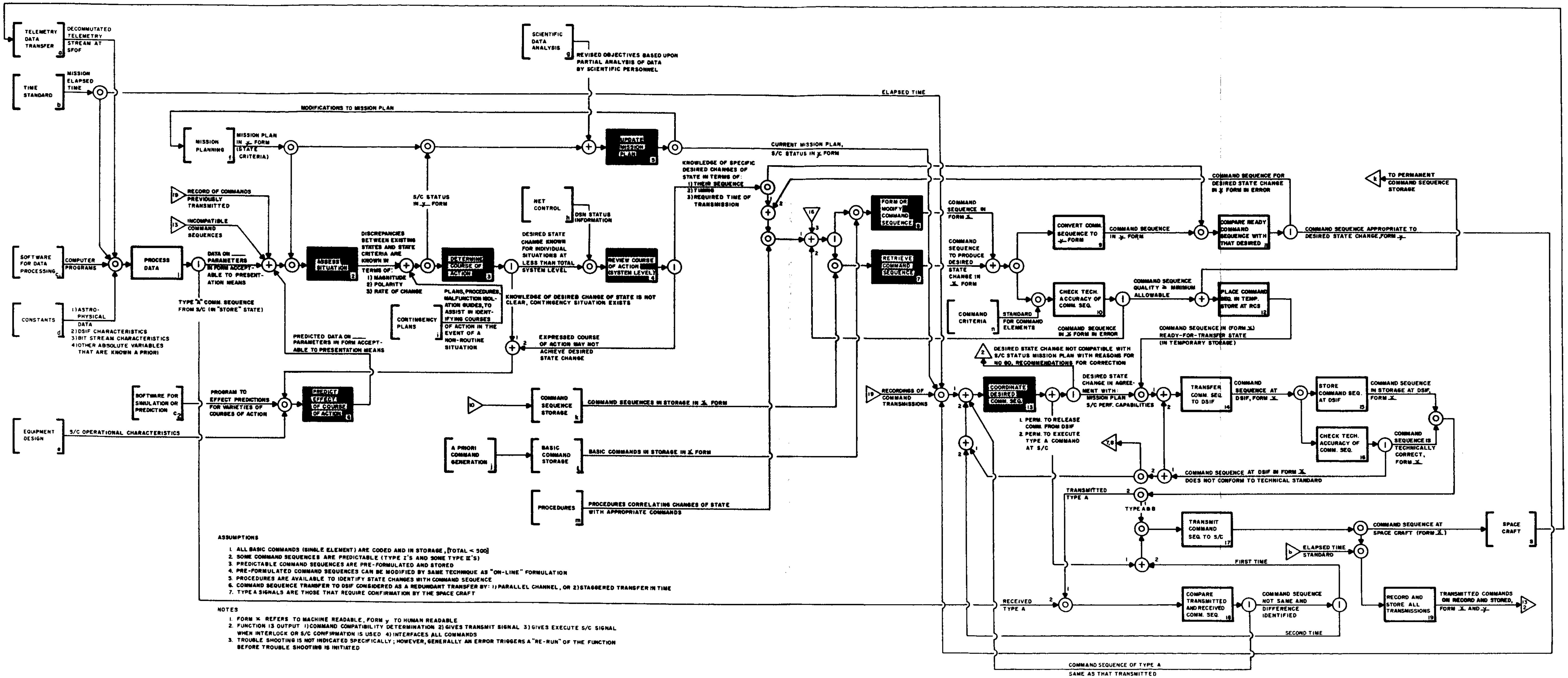

ASSUMPTIONS

1. ALL BASIC COMMANDS (SINGLE ELEMENT) ARE CODED AND IN STORAGE, [TOTAL < 500]
2. SOME COMMAND SEQUENCES ARE PREDICTABLE (TYPE I'S AND SOME TYPE II'S)
3. PREDICTABLE COMMAND SEQUENCES ARE PRE-FORMULATED AND STORED
4. PRE-FORMULATED COMMAND SEQUENCES CAN BE MODIFIED BY SAME TECHNIQUE AS "ON-LINE" FORMULATION
5. PROCEDURES ARE AVAILABLE TO IDENTIFY STATE CHANGES WITH COMMAND SEQUENCE
6. COMMAND SEQUENCE TRANSFER TO DSIF CONSIDERED AS A REDUNDANT TRANSFER BY: 1) PARALLEL CHANNEL, OR 2) STAGGERED TRANSFER IN TIME
7. TYPE A SIGNALS ARE THOSE THAT REQUIRE CONFIRMATION BY THE SPACE CRAFT

NOTES

1. FORM x REFERS TO MACHINE READABLE, FORM y TO HUMAN READABLE
2. FUNCTION 13 OUTPUT 1) COMMAND COMPATIBILITY DETERMINATION 2) GIVES TRANSMIT SIGNAL 3) GIVES EXECUTE S/C SIGNAL WHEN INTERLOCK OR S/C CONFIRMATION IS USED 4) INTERFACES ALL COMMANDS
3. TROUBLE SHOOTING IS NOT INDICATED SPECIFICALLY; HOWEVER, GENERALLY AN ERROR TRIGGERS A "RE-RUN" OF THE FUNCTION BEFORE TROUBLE SHOOTING IS INITIATED

FIGURE 2-14. REMOTE CONTROL STATION FUNCTIONAL CONFIGURATION.

Fold out Frame I

Foldout Frame II

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to facilitate data processing, and various constants which must be taken into account in transforming the data received in raw form from the spacecraft.

The major output state of function 1 also serves as an input state for function 2 (Assess Situation). The basic requirement for function 2 is to assess the status of the various state subclasses (identified in column 1 of tables 2-11 through 2-17, in terms of the parameters specified in column 2 and informational elements identified in column 6) in terms of the discrepancies between the existing states and the required state (identified in column 3). The discrepancies must be identified in terms of magnitude, polarity, and rate of change and must consider the factors identified in column 4 of tables 2-11 through 2-17. In order to meet the requirements, this function will require not only data from the spacecraft, but also mission-plan information (from interface function (s)—Mission Planning). Depending on the circumstances, the function will also require a record of commands previously transmitted from function 19 (Record and Store All Transmissions), information on command sequences which are designated to be incompatible from function 13 (Coordinate Desired Command Sequences), and/or predictions regarding the effect of anticipated command sequences on spacecraft performances from function 6 (Predict Effect of Course of Action). These latter inputs are basically feedbacks resulting from functions implemented subsequent to assessment of the situation but before the command sequences are transmitted to the spacecraft.

If a discrepancy exists between the current state and the required state, function 3 (Determine Course of Action) will be required. The basic requirement for this function is to define the "optimum" course of action to take to resolve the discrepancies between the existing state and the required state. If this definition cannot be accomplished at the required level of confidence, the problem will be designated for further study to determine the potential consequences of alternate courses of action. This latter is the basic NOT state of this function. To accomplish this function, it may be necessary to bring to bear a priori contingency plans from interfacing function (i).

It is anticipated that situation assessment and determination of course of action will be made at varying levels of detail. Consequently, it will be necessary to review individual courses of action for compatibility with other courses of action. This is accomplished in function 4 (Review Course of Action —System Level). The required state of this function is <u>knowledge</u> at the required level of confidence on the specific desired changes of state in terms of (1) their sequence, (2) timing, and (3) required time of transmission. If the confidence level is not sufficiently high, the problem will be designated for further analysis in function 6 to determine the consequences of alternative courses of action.

It is anticipated that the a priori mission plan will have to be changed due to the nature of scientific data collection. Once the system is initiated, information received from the spacecraft system will undoubtedly have a significant effect on establishment of the "optimum" mission plan. Consequently, function 5 (Update Mission Plan) is basically responsible for maintaining a current mission plan. To accomplish this, the function will have information on the status of the spacecraft as well as the original mission plan, and/or changes of objectives resulting from analysis of the scientific data in interfacing function (g)—Scientific Data Analysis.

In support of situation assessment in function 2, function 6 is responsible for providing prediction data on alternate courses of action which will allow reassessment of the situation. To provide the necessary prediction data, this function will require information on spacecraft operational characteristics which will be brought to bear whenever the need for prediction exists. It is assumed that some sort of computer program will be required to allow an effective prediction.

Subsequent to function 4, the courses of action to take will be known, but no command sequences will be available as yet. Consequently, functions 7 and 8 are responsible for providing command sequences. If the command sequences are in storage in interfacing function (k)—Command Sequence Storage, function 7 will be required to retrieve the command sequences. If the command sequences are not in storage in their entirety, function 8 will be required to form or modify the command sequences. The basic commands will be provided through the combination of interfacing functions (j)—A Priori Command Generation and (l)—Basic Command Storage. In either case, the basic state-change requirement is to convert the required courses of action to command states.

The basic requirement for function 9 (Convert Command Sequences to Y Form) is to convert the command sequences provided by functions 7 and/or 8 to a form which can be compared with the desired sequence. This latter comparison is made in function 11 (Compare Ready Command Sequence with that Desired) which will use the courses of action (identified in function 3 and reviewed in function 4) as the basic reference or standard. If the command sequences are not those originally specified in functions 3 and 4, the process of retrieving, or forming, command sequences will be reiterated. If the command sequences are appropriate, the subsequent function will be function 13.

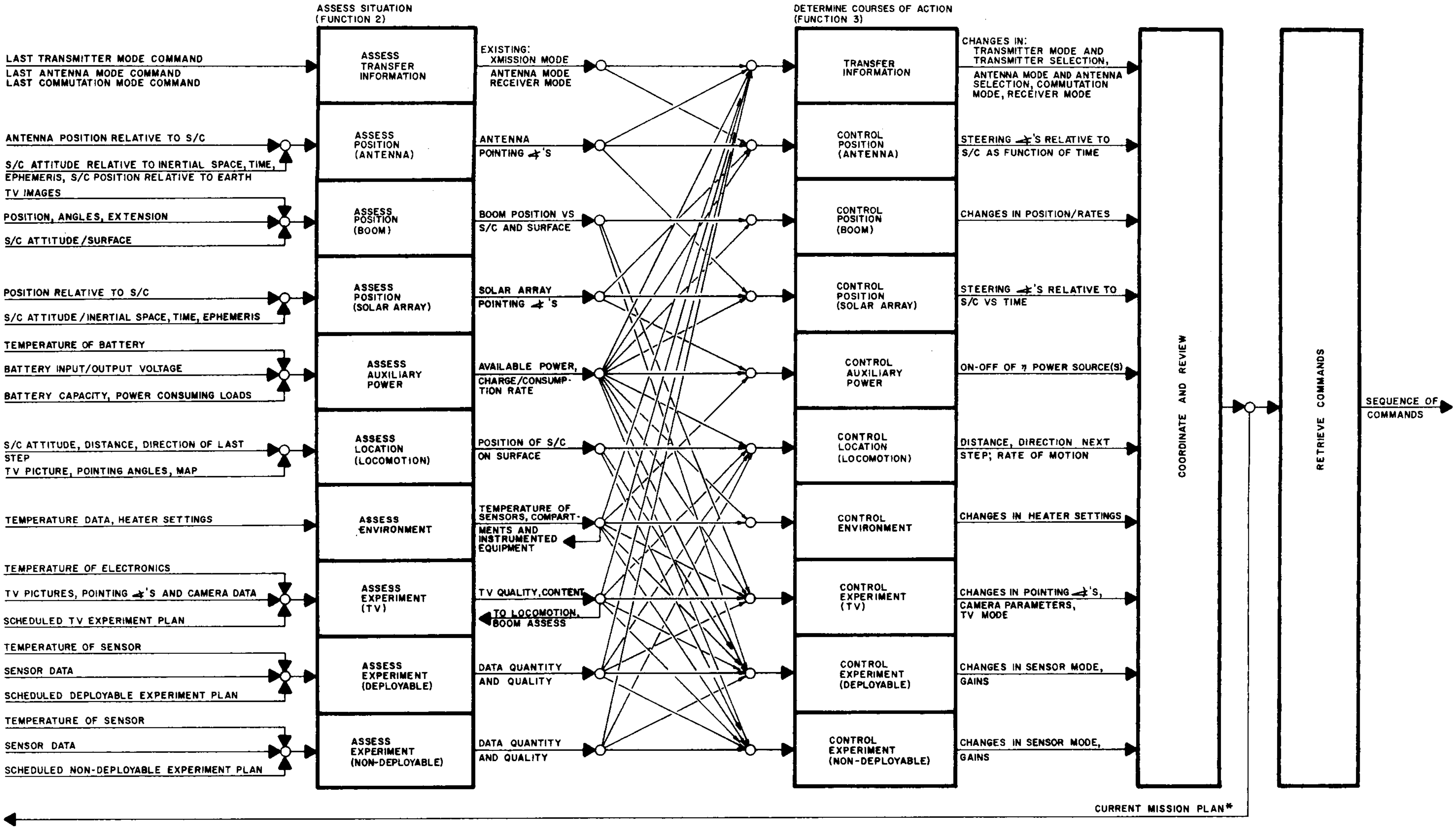
In all cases, it will be necessary to determine that the quality of the command sequences is above a given minimum allowable level. This is accomplished in function 10 (Check Technical Accuracy of Command Sequences) which will use standards provided by interfacing function (n)—Command Criteria. The basic state-change requirement is to change the knowledge state of the quality of command sequences from an unknown state to a known state. The adverse state, or the NOT state, of this function will be when the known (or measured) quality is below the minimum standard. This will result in reiteration of the command retrieval or reforming loop. Note that function 10 does not change the state of commands. It merely changes the state of knowledge about the commands, thereby allowing decisions. These knowledge-changing states (requiring some sort of measurement) are included to assure a minimum level of reliability in the system. Subsequent quantitative assessments may indicate that these functions are not required, or, conversely, that more of these functions are required.

If it is determined that the command sequence quality meets the minimum standard, it will be placed in temporary storage in function 12, and, in certain cases, it will be placed in permanent command sequence storage so that the sequence can be used in similar situations at a later time.

Subsequent to the above functions, the remaining functions will be concerned with changing the location of the command sequences from the RCS to the spacecraft, i.e., transmitting the command sequences. The initial state-change requirement for transmission is to determine that the command sequences designated for transmission are in agreement with both the mission plan and the spacecraft performance capabilities, i.e., they are acceptable to the spacecraft. Although an initial indication of this agreement will be known in function 4, the final knowledge state must be determined after the detailed command sequences have been defined. In order to accomplish this function, it will be necessary to have information on elapsed time, the current mission plan, recordings of previous command transmissions, and the command sequences which need to be transmitted. If the command sequences are not compatible, the entire loop, starting from function 2, will have to be reiterated. If the command sequences are compatible, they will be transferred to the DSIF in function 14 (Transfer Command Sequences to DSIF). The command sequences will be placed in temporary storage at the DSIF in function 15 and again the technical accuracy will be checked in function 16. Incompatibilities of the command sequences will result in either re-initiation of the transfer function in function 14, or repeat of the retrieval or command sequence formation in functions 7 and/or 8.

If the command sequence has not been transmitted before, it will be transmitted in function 17 (Transmit Command Sequence to Spacecraft) and will be recorded and stored in function 19. If the command sequence is one which has been transmitted before, the sequence will be routed to function 18 wherein the command sequence will be compared with the response received from the spacecraft. If the two are compatible, a signal will be sent to the spacecraft to release the command; if not, the signal will be either retransmitted through function 17 or designated for further coordination, depending on whether this is the first occurrence of incompatibility, the second, or a later occurrence.

Examination of the functional configuration in figure 2-14 indicates that functions 2 (Assess Situation) and 3 (Determine Course of Action) account for the major state changes, i.e., change of state from data to knowledge on the required course of action. To identify more specifically the changes of state required for these two major functions, they were partitioned to one lower level of detail. The functions



* MISSION PLAN UPDATE DATA IS PRODUCED BY ASSESS AND DETERMINE COURSE OF ACTION. IT IS COORDINATED AND INTEGRATED AT THE HIGHER LEVEL.

FIGURE 2-15 STATE CHANGE REQUIREMENTS OF THE MAJOR RCS FUNCTIONS were partitioned in parallel fashion since the concern was not with changes of states in sequence, but rather with different changes of states resulting from different spacecraft or scientific-data states. The result of this "parallel" partitioning is presented in figure 2-15. The Coordinate and Review functions and the Retrieve Commands function are presented in an "unpartitioned" manner merely to show the relationships. This lower-order partitioning revealed an interesting result in that the output state (knowledge of the state of a given spacecraft segment) of an Assess Situation subfunction is seldom the only input state required for the subsequent Determine Course of Action subfunction. Knowledge of the status of antenna pointing angles is required knowledge for the Transfer Information, Control Position (Antenna), and Control Position (Solar Array) subfunctions in the Determine Course of Action function. Thus, the partitioning served to indicate the various interrelationships between subfunctions in the Assess Situation function and the subfunctions in the Determine Course of Action function.

The criterion for partitioning functions 2 and 3 was basically the differences of the state changes resulting from various categories of spacecraft or scientific-data states. These state-change categories correlate quite well with the spacecraft state classes, or the six major spacecraft functions identified in the previous section. There are some differences, however, in that the position states are divided into three classes and the scientific data states are grouped into three classes. Position states are divided into antenna positions, boom positions, and solar array positions. The scientific data states are grouped into TV data, data on experiments using the deployable sensors, and data on experiments using nondeployable sensors. The rationale for this separation is strictly judgmental and, as stated before, based primarily on anticipations of different state changes required within the RCS.

Further Delimitations of the RCS

Initial analysis of the functions delineated in figure 2-14 indicated that (1) time would not permit a reasonable level of design analysis of all the functions, (2) analysis of some of the functions would merely serve to "define the obvious" since JPL has had considerable experience in successfully implementing similar functions (e.g., data processing and converting the data form), and (3) the major state changes were accomplished by a relatively small number of functions. Therefore, a decision was made to limit the RCS to (1) those functions effecting the major changes of state and (2) those functions interacting directly with the functions accounting for the major changes of state and could not be treated apart from them.

As indicated previously, the major changes of state within the functional configuration in figure 2-14 occur through the combination of functions 2 (Assess Situation) and 3 (Determine Course of Action). Through these two functions, a set of data states is transformed into knowledge of corrective actions required. Thus, functions 2 and 3 were selected as the core functions of the RCS. Function 6 (Predict Effect of Course of Action) was selected for inclusion since it is basically a subset of function 3. Function 5 (Update Mission Plan) was included due to the anticipated need to adjust the total plan on the basis of current situations. It was anticipated that many missions would be initiated without specific hypotheses to test and the conduct of the mission would depend on the specific situations as they are assessed. The Review (4) and Coordinate (13) functions were included to account for integration of subsets of decisions into a single set (system level). The command retrieval (7) and formation (8) functions were included to (1) assure transformation of "knowledge" into commands, and (2) account for RCS-peculiar requirements for command retrieval and/or formation.

A general block diagram of the eight functions selected for inclusion in the RCS is presented in figure 2-16. Details are not provided since the state definitions are provided in figures 2-14 and 2-15.

Functional RCS Requirements

The functional RCS requirements refer to the performances required of individual RCS functions. These represent the lowest order of requirements presented in this report. So the reader will not be disappointed, it should be noted that detailed descriptions of performances required within each function are not presented. This lack of detail is partially by design and partially due to lack of time in the study.

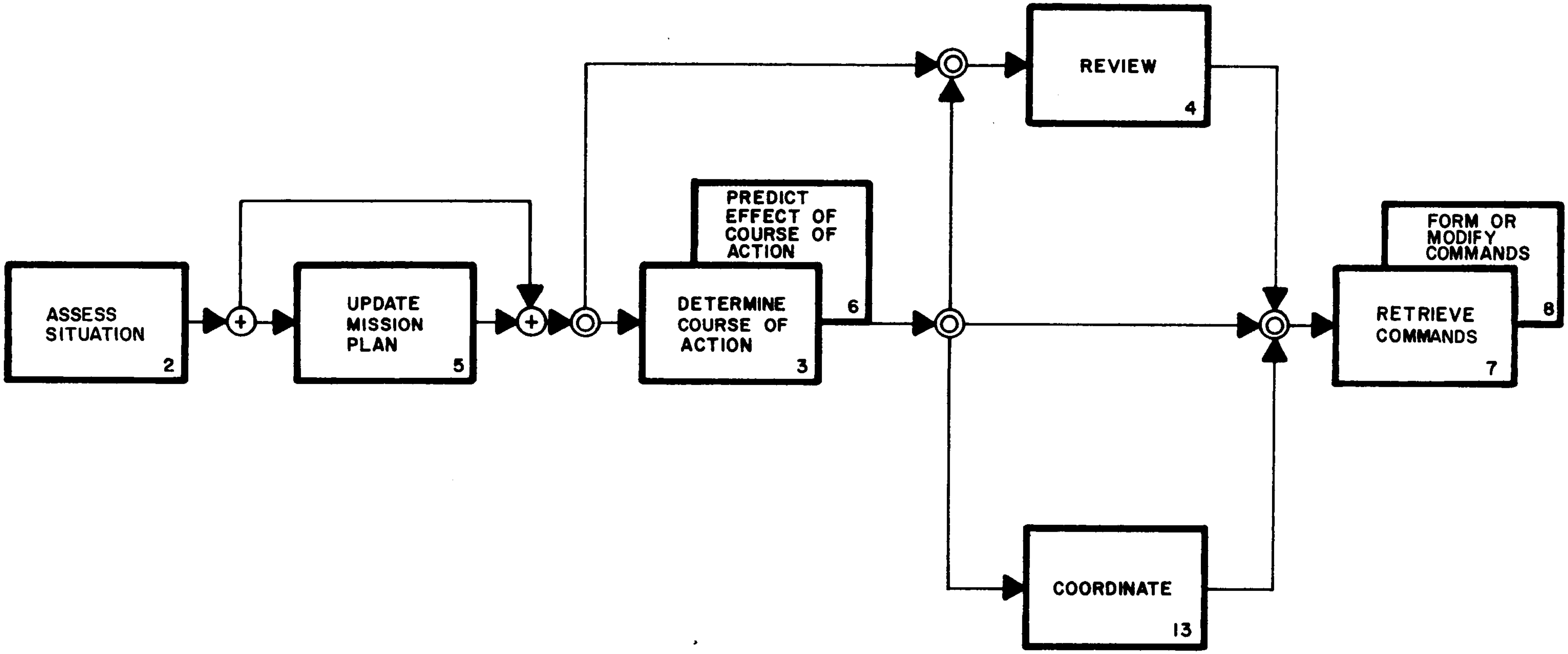


FIGURE 2-16 FUNCTIONS TREATED AS RESPONSIBILITY OF RCS

The specific performances required within each function must be based on the specific class of mechanism used in individual spacecraft systems and quantitative values assigned to the state parameters bounding each function. Although an attempt was made, it was not possible to develop a comprehensive list of candidate spacecraft mechanisms within the scope of this study, or to assign quantitative values to the state parameters. This meant that detailed analysis of the individual RCS functions would not be cost effective at this time.

Even though a detailed analysis of the functions was not possible, some additional analysis was necessary to allow initial development of the conceptual design. Since the state-change requirements define the basic requirements for a function, it is evident that further definition of the function is required only if the state-change requirements do not provide sufficient details to allow allocation of physical means to the functions. Furthermore, the lack of quantitative requirements means that emphasis at this time should be placed on the information required for qualitative assignment of physical means based on engineering judgment rather than a cost-effective assignment.

The combination of the command/control requirements in tables 2-11 through 2-17 and the detailed flow diagram for functions 2 and 3 (figure 2-15) provided considerable details on the state-change requirements of the key RCS functions. Rather than repeat the same state-change information, it was decided to concentrate on identifying the basic characteristics of the states relevant to the RCS functions and the factors which could affect performances within the function. This analysis was conducted for all the functions identified in figure 2-14, primarily because it was conducted before certain functions were eliminated from RCS considerations. In the event that the data might be useful to JPL, the data for all the functions are presented in table 2-19. Only functions 2, 3, 4, 5, 6, 7, 8, and 13 are of concern to the RCS.

Note that the input and output states are treated only in general terms. More detailed definitions of these states may be obtained from tables 2-11 through 2-17. The state characteristics are expansions (where necessary) of the state definitions provided in figure 2-14. The major contributions of table 2-19 are represented in the final column, i.e., factors affecting functional performance. Although the entries are judgmental, they proved to be useful since the judgments were based on detailed considerations of the types of performances required within each function.

As a final step in defining the functional requirements, a general description of each of the eight RCS functions is provided. These descriptions represent a summary of the types of performances assumed in identifying the "factors affecting function performance" for table 2-19.

Assess Situation (2)

The term "assess" means to estimate, appraise, or evaluate. In the context used here, assessment is defined as the act of estimating the true state of the system or spacecraft function under concern. The assessment function requires access to incoming telemetry data on the parameters relevant to the system state of concern, a priori knowledge of the mechanical, electronic, or chemical structure of the spacecraft means, information correlating a particular state with cues received by telemetry data or by other means (e.g., simulation where direct observation is possible may display behavior patterns not discernible from telemetry alone); however, if the patterns are repeatable, auxiliary cues, such as response rate, might aid assessment. The assessment function may be as simple as observing quantitative data received from the spacecraft and concluding that this data represents the state of the system of concern, such as the temperature of a sensor. On the other hand, assessment can become a highly judgmental function. Contingency situations present the assessment function with its most demanding requirement. The anticipated complexity of this function has previously been defined, page 2-42. A certain degree of analysis is usually required to adequately assess a state. Therefore, analytical means are necessary for the assessment function. During this function, no attempt is made to predict what new state would occur if a particular course of action is taken, nor to determine how to achieve a specified state. This requirement is accomplished under an allied function, termed "Determine Course of Action."

Table 2-19. RCS Functions Description.

Function	States		State Characteristics	Factors Affecting Function Performance
	Input	Output		
1. Process Data	1.1 Telemetry stream from spacecraft (demodulated and decommutated)			a. processing accuracy 1) reliability 2) confidence b. processing resources availability c. processing time d. number of simultaneous processing requirements c. acceptability of output to presentation means (buffer requirements)
	a. Engineering data		a. quantity of data b. quality of data (error rate) c. rate (b.p.s.) d. number of parameters	
	b. Scientific data		a. quantity of data b. quality of data c. rate (b.p.s.)	
	1.2 Elapsed time		a. accuracy—rubidium standard (units of hours, minutes, seconds) b. base, i.e., GMT, elapsed time, local time, etc.	
	1.3 A priori knowledge a. Ephemeris b. DSN characteristics c. S/C characteristics d. RCS characteristics e. SFOF characteristics		a. thermal characteristics b. limits/capabilities of system c. power consumption d. transmission/reception modes	
	1.4 Computer Routines a. Power model b. Thermal model c. Planetary model d. Other models		a. computations required to produce output b. core storage required	
		1.5 Data on desired parameters in form acceptable for situation assessment	a. classification of parameters b. range of parameter c. change of parameter	

Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
			d. number of parameters e. form of processed parameter	
		AND		
		1.6 Data on status of command sequence, "Type A," in store at spacecraft requiring comfirmation (command type A)	a. acceptable to command sequence comparator such as proposed CVE b. command sequence not necessarily routed via data processing at RCS; if not signal required for information	
2. Assess Situation	2.1 Output from Data Processing Function in form acceptable to presentation means		a. parameters presented by S/C function, S/C system, or other classification dependent upon organization of RCS b. quantity of parameters c. quality of parameters d. representativeness	a. time available (allowed) for performance b. number of parameters required for assessment c. presentation mode d. availability and specificity of plan e. compatibility of state expression in mission plan & telemetered (processed) data f. confidence in plan g. computation requirement to to determine status h. number of expected contingencies i. time rate of change of parameters j. S/C status information availability 1) time 2) accessibility k. detectability of required information l. criticality of S/C state m. scientific data 1) complexity of experimental design 2) sequence (fixed or variable) of data collection
	2.2 Mission Plan		a. basis of mission plan (state, events, temporal) b. number of mission objectives c. number of alternatives d. ordering of mission objectives e. accuracy f. criteria/standards 1) format 2) tolerance 3) range 4) number of standards	
	2.3 Previous command transmissions		a. commands identified by: 1) effect on S/C 2) time of execution or transmission b. DSIF site of transmission	

Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
	2.4 Incompatible commands		a. command I. D. b. reason for incompatibility c. recommendations from rejecting source	3) form of available data n. relationship between command element and its effect (desired state) 1) availability 2) form 3) detectability of command element and its effect
	2.5 Predictive data on system operation		Same as 2.1	
		2.6 Discrepancies between existing and desired states on S/C function, subsystems, or parameter under consideration AND	a. magnitude b. polarity c. rate of change	
		2.7 Spacecraft status	Same as 2.7 except in form suitable for: a. revision of mission plan b. release of status information	
3. Determine Course of Action	3.1 Output(s) from Assess Situation Function 3.2 Contingency plans and procedures		Discrepancies between existing and desired states expressed a. malfunction isolation guides b. procedures c. checklists d. compatible with form 3.1	a. time available (allowed) for performance b. format of procedures c. presentation mode d. availability and specificity of plan e. confidence in plan f. number of expected contingencies g. assessment information availability 1) time 2) accessibility h. detectability of required information i. criticality of S/C state j. scientific data 1) complexity of experimental design
		3.3 Desired State Changes expressed OR	Specification of action required to effect desired state(s)	
		3.4 Recommendation to exercise "Predict effect of Course of Action" Function	a. analysis b. consultation c. simulation 1) computer 2) hard copy	

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Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
				2) sequence (fixed or variable) of data collection 3) form of available data k. relationship between command element and its effect (desired state) 1) availability 2) form 3) detectability of command element and its effect
4. Review Course of Action	4.1 Recommended course(s) of action		Specification of action required to effect desired state(s)	a. number of classes of information for which responsible b. rate at which review must be made c. time available for each performance d. specificity of recommended courses of action e. criticality of decision f. confidence in courses of action recommended by specialty groups g. authority in organizational structure
	4.2 DSN status information		a. GCS operational status b. DSIF operational status c. support systems availability	
		4.3 Knowledge of specific desired change(s) of state	a. command sequence b. command timing c. time of transmission	
		OR		
		4.4 Knowledge that recommended course of action may not achieve desired state change	a. reason for incompatibility b. recommendation for alteration or method to obtain correct course of action	
5. Update Mission Plan	5.1 Original mission plan		Same as 2.2	a. mission plan format b. specificity of mission plans c. availability (accessibility) of mission plans d. timeliness of mission results e. timeliness of spacecraft status
	5.2 Status of S/C and data collection equipment		a. remaining S/C resources b. malfunctions within S/C c. remaining available time for data collection	
	5.3 Revised objectives resulting from data analysis		a. quantity of data b. representativitv of data points c. unexpected results from scientific data	

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Table 2-19. RCS Functions Description (Continued).

Function	States		State Characteristics	Factors Affecting Function Performance
	Input	Output		
		5.4 Mission plans revised to conform with dynamic situation	a. revisions in objectives b. alterations in tolerances, ranges, rates c. changes in time allowed for objectives	
6. Predict Effect of Course of Action	6.1 Computer software		a. prediction by analysis b. simulation by computer c. simulation by hardware model	a. computations required b. number of alternate courses of action c. criticality of decision d. sufficiency of status information e. time available f. required confidence in prediction
	6.2 Requirement to conduct prediction activity		a. contingency exists b. unknown environmental effects suspected c. equipment malfunction d. alternate courses of action not quantified	
		6.3 Data relating to predicting effect of selected course(s) of action	Data on: a. optimal course of action b. effect of proposed course of action c. potential command sequences to achieve desired state	
7. Retrieve Command Sequence	7.1 Output of "Review Course of Action" Function		Same as 4.3	a. allowable retrieval time b. accuracy of retrieval process c. number of sequences in storage d. similarities and dissimilarities of sequences in terms of elements within sequence and their ordering e. correspondence between sequence identity and retrieval action
	7.2 Command sequences in storage,		a. address (identification) b. form in which stored 1) command element 2) command unit 3) command sequence c. number of identifiable commands in storage d. accuracy of storage	
	7.3 Retrieval system operational instructions		a. form b. accessibility c. accuracy	

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Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
			d. completeness e. maintainability	
		7.4 Desired command(s)/command sequence(s)	a. command format b. ordering of commands c. timing of command d. accuracy of sequence e. effect of sequence	
8. Form or Modify Command Sequence	8.1 Output of "Review Course of Action" Function		Same as 4.3	a. command generator characteristics 1) operating instructions 2) rate 3) accuracy b. similarity between 1) command elements 2) command sequences c. allowable formation time d. similarities and dissimilarities of sequences in terms of elements within sequence and their ordering e. correspondence between sequence identity and retrieval action f. number of elements within sequence g. ordering of command elements h. timing within command sequence 1) time length 2) physical length i. accuracy of formulated sequence
	8.2 Command sequence error is known		a. location of error b. type of error 1) formatting 2) ordering 3) timing 4) omissions 5) extraneous entry	
	8.3 Basic commands in storage		a. number of basic commands b. length of basic command c. storage capacity d. reception rate e. accuracy of storage f. storage environment	
	8.4 Command formulation system operating instructions		a. form b. accessibility c. completeness d. accuracy e. maintainability	
		8.5 Desired command(s)/command sequence(s)	a. command format b. ordering of commands c. timing of command d. accuracy of sequence e. effect of sequence	

Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
9. Convert Command Sequence Form	9.1 Command sequence, formulated or retrieved in machine readable form (form x)		Form x not compatible with form y without conversion	a. mission plan format b. desired state change format from Function 3 c. number of command sequences d. command sequence expressed so that it may be compared with the desired command e. time required for performance f. accuracy of conversion
		9.2 Command sequence available in human readable form (form y)	Human readable (or in same form as: a. mission plan b. state required expression	
10. & 11. Compare Available Command Sequence with Desired Command Sequence	10.1 Command sequence as desired		Same as 4.3	a. type of error discriminator b. accuracy of error discriminator c. rate of discrimination d. number of separate elements in command sequence e. number of command sequences f. time available for comparison g. criticality of performance h. accuracy of comparison
	10.2 Command sequence as available		Same as 9.2	
		10.3 Errors between available and desired command sequence(s)	a. discrepancies are noted and presented in human readable format and machine language b. extent of error 1) formatting 2) sequence 3) timing	
12. Place Command(s)/ Command Sequence(s) in Temporary Storage	12.1 Verified command sequence in form x available		Probability of error considered in placing in storage	a. number of sequences b. length of sequence c. type of storage d. identification of sequence in store e. duration of storage f. performance time g. accuracy requirements
		12.2 Command sequence in store in form x	Probability of error considered in maintaining basic command storage	
13. Coordinate Command Sequences	13.1 Desired command sequence(s)		Form y received from function 11	a. criticality of command request b. form in which requests are presented c. safeguards on execution signals to: 1 1) release command to DSIF 2) release command to S/C 3) execute command at S/C
	13.2 Mission plan		Same as 2.2 except all inclusive	
	13.3 Elapsed time		Same as 1.2	
	13.4 Identification of errors or contingencies		a. command format errors b. transmission errors c. S/C contingencies	

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Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
	13.5 DSN status		a. DSIF system status b. GCS support status c. personnel status	d. command sequences 1) number 2) length 3) type e. time delay 1) processing 2) transit f. technique of coordination g. coordination accuracy h. authority in organizational structure i. performance time
	13.6 Historical records		a. previous transmission b. S/C status c. scientific data status	
		13.7 Signal permitting command transmission a. to DSIF b. to S/C c. to execute command at S/C	a. signal form b. accuracy of signal	
		— OR —		
		13.8 Notation of incompatibility of requested command sequence	a. extent of conflict or error b. recommendation for solution c. reallocation of resources	
14. Transfer Command Sequence to DSIF	14.1 Confirmed command sequence		Same as 12.2	a. number of transmissions b. availability of transmission facilities c. status of GCS d. transmission accuracy e. performance time
	14.2 Signal allowing transfer		Same as 13.7	
		14.3 Command sequence transmitted to DSIF in form x	Same as 12.2	
15. Store Command Sequence at DSIF	15.1 Command sequence from RCS in form x		Same as Function 12.1	a. storage time b. accuracy of storage process c. number of sequences in storage d. similarities and dissimilarities of sequences in terms of elements within sequence and their ordering
		15.2 Command sequence in storage at DSIF	a. address (identification) b. form in which stored 1) command element 2) command unit 3) command sequence	

Table 2-19. RCS Functions Description (Continued).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
			c. number of identifiable commands in storage d. accuracy of storage	e. correspondence between sequence identity and retrieval action
16. Check Technical Accuracy of Command Sequence	16.1 Command sequence in store of quality unknown		a. command checked by: 1) redundant transmission 2) stored standard b. check made in x form	a. type of error discriminator b. accuracy of error discriminator c. rate of discrimination d. quantity of commands processed e. comparator similar to proposed CVE or to means for function 11 f. performance time
		16.2 Command sequence in store	a. number of command elements b. address (identification) c. storage accuracy d. stored in form x	
		16.3 Difference in command sequence noted	Number and extent of errors in: a. sequence b. timing c. format	
17. Transmit Command(s)/ Command Sequence(s) to Spacecraft	17.1 Command sequence in store at DSIF		Same as 16.2	a. number of command sequences in storage b. Idnetification of correct stored sequence c. retrieval time d. view window e. DSIF status f. transmission rate acceptable to S/C g. transmission accuracy
	17.2 Signal from RCS "Coordinate Command Sequence Function" to transmit or execute command		Same as 13.7	
		17.3 Command sequences transmitted to S/C	If confirmation is required storage and retransmission at S/C required, Type A commands only	
18. Compare Transmitted and Received Command Sequence	18.1 Command sequence received from S/C		a. in form x b. quality at DSIF/S/C uncertain c. type A commands only	a. number of confirmations required b. identification of command sequence in storage to compare received signal c. view window d. retransmission rate
	18.2 Command sequence in storage at DSIF		Same as 16.2	

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Table 2-19. RCS Functions Description (Concluded).

Function	States: Input	States: Output	State Characteristics	Factors Affecting Function Performance
		18.3 Error between signals transmitted and received	a. error identification b. error type c. error extent	e. storage time at S/C f. storage of received signal required g. errors noted in form x and y h. performance time
19. Record and Store all Transmissions	19.1 All command transmissions		Transmission in x form	a. type of storage 1) paper printout 2) magnetic tape b. distribution c. compatibility with S/C event historical records d. means may be combined with means for functions 15, 16, and 18
		19.2 Command transmissions recorded and stored	a. recorded chronologically b. available in y form c. expected state change d. DSIF I. D. e. time of transmission	

Determine Course of Action (3)

This function is defined as the act of specifying, or designating, the steps to take to change the existing state of a spacecraft system or function to another specified state. The specified state, usually a desired state called for as a result of a preplanned mission schedule, is compared to the existing state and a course of action designated, or proposed, to accomplish the change. This function requires for its accomplishment:

1. Historical data on the performance of the subject spacecraft mechanism or function under similar circumstances;
2. Experimental objectives or desires that involve the system or function in question in terms that permit identification of desired states;
3. Constraints in terms meaningful to the spacecraft system or function on resource utilization, time availabilities, and restricted electronic or mechanical courses of action; and
4. The results of the assessment function identifying the existing state.

The results of the Determine Course of Action function may be to recommend that nothing be done for a specified length of time, or until a particular state is achieved, e.g., a given amount of data are received from the present configuration. Other results of this function may be to recommend that particular steps be executed by means of transmitted commands to the spacecraft, or that exercises should be conducted to predict what would happen in the event a selected course of action were followed.

Predict Course of Action (6)

When it is not possible to determine what course of action should be taken with a sufficiently high confidence level, certain exercises may be required to gain a higher degree of confidence. These exercises may take the form of computer programs simulating the behavior of the spacecraft function or system under study, manipulation of a hardware model of the spacecraft system or portions thereof, or consultation with specialty groups that are more familiar with the operational characteristics of the spacecraft than are the Remote Control Station operators. It is anticipated that the requirement for this function will occur most frequently during contingency situations where little experience from similar situations can be brought to bear. The function may also be used prior to state-change execution to prepare certain courses of action based upon a given existing and desired state. The result of this function used in this manner would be prepared operational sequences (reduced to command sequences) for use during the mission.

Update Mission Plan (5)

Mission plans are assumed to exist at varying levels of detail prior to mission execution. Since all eventualities cannot be anticipated, it is certain that modifications to the original plan will be required. Much of the data for mission plan alteration will be derived from the Assess function where information is gained on what kind of data have been obtained, the state of the spacecraft during data-gathering activities, and the remaining capabilities to follow out the mission plan. The results of this function may be to alter the time consumed in performing a specific spacecraft function since the primary objectives may have been met, while other specified objectives have been determined to require more time than originally allocated. Unexpected scientific data may indicate that the previously designated priorities should be revised, and greater effort given to exploiting the unforeseen situation. Although a requirement for the mission plan updating function can be foreseen, the specific changes or recommendations resulting from the function are only determinable during the course of the mission.

Review (4)

The Review function may formally occur at two different echelons of responsibility and at two different stages of the control process. One review is assumed to be conducted by the performing level within the RCS. Prior to submitting the results of a function, whether it be assessment, determine course of action, etc., the result is assumed to be checked, reviewed, or validated. Another level of review may be conducted by a higher echelon who has a view of the total spacecraft operation. This review is considered mandatory for certain courses of action. If a course of action can result in spacecraft damage, significant data loss, or other adverse, irreversible states, a formal review prior to execution appears to be in order. Standard operating procedures delineating the commands and courses of action open to local option should be used to guide operators in this regard. These reviews may be conducted prior to or after the command sequences have been retrieved to execute the proposed course of action. It is probably more satisfactory, from a reliability standpoint, to review the proposed course of action <u>and</u> the command sequence.

Coordinate (13)

This is a function that might also be termed "cooperate." In a system as complex as the control of a spacecraft, many simultaneous activities will undoubtedly take place. In order to operate as a system, all parts must contribute to the same objectives. When several people are involved, or several machines are operated concurrently, coordination is required. Although the functional responsibility of coordination may lie within the project management echelons, lateral communication is assumed throughout the RCS as required by the operating personnel. Coordination involves keeping personnel aware of conditions and events that may impact their performance. Direction is implied in the context that coordination is used here; thus, this function should be considered together with review.

Retrieve Commands (7)

Once the course of action has been determined, the appropriate commands to execute that action must be retrieved. The Retrieve Commands function is responsible for obtaining proper commands, properly sequenced and timed, so that the course of action may be executed. As previously stated, this function may occur prior to a review to determine the compatibility of the course of action with the desired result. It is assumed that all individual commands will be held in storage so that as a result of a particular action (on the part of man or computer) a specific command (or series of commands) is retrieved and prepared for transmission. Where a sequence of commands can be associated with a course of action a priori (many courses of action can be predicted in advance), a string of commands can be addressed by a single signal. Preparatory and terminating commands can be programmed into the command retrieval system if they can be associated with the initiating command address. It is anticipated that many routine state changes can be handled in this manner.

Formulate Command Sequence (8)

The act of sequencing multiple commands into a sequence to execute a course of action is termed "Formulate Command Sequence." This function may be accomplished by a computer program given certain initiating signals, or it can be performed by man addressing individual commands in the sequence required to execute the desired state change. This function assumes the Retrieve Command function capability, and the means to accomplish it may be synthesized with the previous function. Certain situations requiring qualitative decisions or judgments of man dictate that command sequence formulation be performed incrementally. Thus, two levels of command formulation capability will be required. One is based on a computer with appropriately designed software to generate the command retrieval signals, while the other is based on a man performing this function. The output of each means may be generated prior to its use and stored until such time as it is needed. Once the command sequence for a particular course of action has been secured, it may be transferred to the DSIF for immediate or subsequent transmission.

SYSTEM-EFFECTIVENESS CONSIDERATIONS

Current interest in the concept of system effectiveness is the result of an evolutionary process which began with the realization that simple measures of performance were oftentimes inadequate and inaccurate estimates of the worth of complex systems. For example, an aircraft which has excellent speed range and payload may be very ineffective due to its inability to deliver its payload on the target (the B-70, for example). Because of difficulties such as these, the concept of performance measurement has evolved to the point where it is now accepted by many that system effectiveness is a measure of the degree to which system objectives are achieved. Examples of such measures are Circle of Error Probability (CEP), probability of intercept and destroy, and flying hours per aircraft month (in the case of a transport aircraft). Some general criteria for measures of effectiveness are:

1. Relatability to higher-level objectives.

2. Consistency with the authority and responsibility of the group performing the analysis (i.e., don't ask a design engineer to increase the knowledge of the universe by "X%").

3. Measurability.

To apply the system-effectiveness concepts to the RCS, the objectives of the system must be defined. Some have questioned the necessity to use the data objectives defined in earlier sections of this chapter as the objectives for the RCS. They have suggested that the objective of the RCS is to control the unmanned spacecraft. This raises the question of how to measure the degree to which this objective is achieved. It might be said that control is successful as long as the spacecraft is doing what is desired of it. If this is acceptable, then is it not true that the true objective of the RCS is to make the spacecraft do what is desired.

Assume for the moment, however, that the objective of the RCS is to send control signals to the spacecraft. Intuitively, it might be said that this objective is achieved as long as we send these control signals where we desire to send them, and that the signals sent are, in fact, those which we should have sent. Basically, these factors are measures of time and reliability. Before adopting this approach, however, it should be reviewed in light of the criteria for effectiveness measures. If it is agreed that these criteria are in fact valid, then it is not too difficult to show that the above-mentioned effectiveness measures are not the most useful. First, how are these measures relatable to higher-level objectives (criterion 1) unless we know the effect of variations in timing and reliability? This is felt to be the most glaring deficiency of such an approach. Secondly, in order to send the proper control signals to the spacecraft, one must know something of the spacecraft status and the desired states. Measures to determine the degree to which the data-collection objectives have been met depend upon criteria by which to measure the accomplishment of these objectives. Therefore, effectiveness definition is contingent upon a definition of the spacecraft objectives.

Because of these and other difficulties inherent in using narrow measures of effectiveness for the RCS, it has been concluded that since the true objective of the RCS is to guide the spacecraft in the execution of certain tasks, measures of effectiveness of the RCS should reflect the degree to which this objective is achieved. This approach does not preclude the possibility of arriving at a standard set of RCS criteria independent of specific spacecraft objectives; however, it does not appear that such a standard set could be obtained without somehow relating RCS performance to spacecraft performance at the outset.

Relating RCS Performance to Spacecraft Performance

Based on the assumption that the objective of the spacecraft is to obtain information through the execution of certain experiments, the relative effectiveness of the RCS might be expressed as follows

$$E_{RCS} = f\left(a_1 \frac{\hat{x}_1}{x_1},\ a_2 \frac{\hat{x}_2}{x_2},\ a_3 \frac{\hat{x}_3}{x_3},\ \dots\ a_n \frac{\hat{x}_n}{x_n}\right) \qquad (1)$$

where

x_i = a measure of the information required from the ith experiment, given an optimal plan, no contingencies, and no time delays or errors in the RCS. The x_i may be a number of samples, a measure of confidence, or area coverage; however, these must be obtained from those responsible for experimentation.

$\hat{x}_i$ = a measure of the information obtained from the ith experiment, given that the RCS is in the loop.

a_i = weighting factor of the ith experiment.

If the function described by (1) is linear, effectiveness could be described as follows

$$E_{RCS} = a_1 \frac{\hat{x}_1}{x_1} + a_2 \frac{\hat{x}_2}{x_2} + a_3 \frac{\hat{x}_3}{x_3} + \dots\ a_n \frac{\hat{x}_n}{x_n}$$

and, if $\sum_{i=1}^{n} a_i = 1$, Max $E_{RCS} = 1$ and Min $E_{RCS} = 0$

In other words, the relative effectiveness of the RCS would be expressed as a nondimensional variable ranging from 0 to 1.

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Candidate Effectiveness Measures

The above indicates that the proper selection of x_i is crucial to a development of a useful system-effectiveness measurement/assessment approach. Candidate criteria parameters are discussed in this subsection along with approaches to measuring the parameters. The specific parameters and measurements will depend on the purpose of individual experiment types, availability of information on candidate mission plans, and information on similar experiments. Thus, the final selection is anticipated to be an integral part of implementing the general approach discussed in this chapter.

In order to establish candidate effectiveness criteria, it was assumed that each of the planet state characteristics (about which data are required) has a true (but unknown) mean value, and that the purpose of a typical mission is to provide estimates for k of these characteristics, which have the true mean values, $\mu_1, \mu_2, \ldots, \mu_k$.

It was further assumed that, because of limited resources and spacecraft life expectancy, the mission plan will call for allocating times to the k experiments: $T_1, T_2, \ldots, T_k$. For initial allocation purposes, these times can be allocated independently of any consideration of RCS delays or errors, i.e., a perfect RCS can be assumed. For those experiments involving discrete measurements, these time allocations result in a specification of the number of samples taken for each experiment. If t_i is the time for one sample of the ith type experiment,

$$n_i = \frac{T_i}{t_i} \tag{1}$$

is the number of data samples for the ith experiment.

The n_i observations of characteristic i allow an estimate of the value of μ_i. This estimate is

$$\bar{x}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij} \tag{2}$$

where the values x_{ij} represent the successive measurements of characteristic i.

A Vector Measure of Effectiveness

One possible measure of the effectiveness of the data-collection mission in fulfilling its objective is the accuracy with which the estimate $\bar{x}_i$ represents the true values μ_i. For example, one objective function for the ith experiment might be

$$OF_1 \ (i) = E \left[\left| \bar{x}_i - \mu_i \right| \right] \tag{3}$$

which is the expected value of the absolute error, given n_i observations are made for experiment i.

Other possible objective functions include the expected percentage error:

$$OF_2 \ (i) = E \left[\frac{\left| \bar{x}_i - \mu_i \right|}{\mu_i} \right] \tag{4}$$

and the expected squared error:

$$OF_3 \ (i) = E \left[(\bar{x}_i - \mu_i)^2 \right] \tag{5}$$

Whichever of the above measures is used (if any), the result will be a vector representation of the effectiveness:

$$M_p = \left[OF\ (1),\ OF\ (2),\ \ldots,\ OF\ (k) \right] \tag{6}$$

A Single Measure of Effectiveness

If a single index of effectiveness is required, weighting values w_i can be used to represent the relative importance of the different experiments to the overall data-collection mission. In this case, the above objective functions become

$$OF_1 = \sum_{i=1}^{k} E \left[x_i - \mu_i \right] w_i \tag{7}$$

$$OF_2 = \sum_{i=1}^{k} E \left[\frac{\bar{x}_i - \mu_i}{\mu_i} \right] w_i \tag{8}$$

$$OF_3 = \sum_{i=1}^{k} E \left[(\bar{x}_i - \mu_i)^2 \right] w_i \tag{9}$$

$$0 \leq w_i \leq 1$$

For example, if OF_2 is used, the objective function is the average percentage error of the experimental measurements, where each experiment is weighted according to its importance. (If all experiments are regarded equally important, $w_i = \frac{1}{k}$ for each i.)

Effectiveness of Imperfect RCS

Let us assume we have chosen an objective function, say OF_1, and consider now the case of an imperfect RCS, with time delays and possibly erroneous decisions and commands. An analysis of RCS functions shows that due to time delays and certain kinds of errors, lost time for performing the k experiments will have expected values ΔT_1, ΔT_2, ..., ΔT_k. This will leave the available time for performing experiments reduced; for the ith experiment, the available time is $T_i - \Delta T_i$. This, in turn, will result in a reduced number of observations and hence increased error in the estimates. (For nondiscrete observations it will also be assumed that the error increases inversely with the time available for observation.) Also, certain types of errors in the RCS will degrade the accuracy of the measurements x_{ij}.

The number of observations for the ith experiment now becomes n_i', where

$$n_i' = \frac{T_i - \Delta T_i}{t_i} \tag{10}$$

and for each experiment $n_i' \leq n_i$. We also have

$$\bar{x}_i' = \frac{1}{n_i'} \sum_{j=1}^{n_i'} x_{ij} \tag{11}$$

and the objective function corresponding to equation (3), for each experiment i, becomes

$$OF_1 \ (i)' = E\left[\bar{x}_i' - \mu_i\right] \tag{12}$$

The vector measure of effectiveness for an imperfect RCS, corresponding to equation (6), is

$$M_I = \left[OF\ (1)', OF\ (2)', \ldots, OF\ (k)'\right] \tag{13}$$

The scalar objective functions OF_1', OF_2' and OF_3' for an imperfect RCS, corresponding to equations (7), (8) and (9) are similarly obtained by substituting $\bar{x}_i'$ for $\bar{x}_i$.

Relative Effectiveness

The objective functions measure errors of estimation, thus small values are desirable. For an imperfect RCS, the expected errors will always be larger than for a perfect RCS, i.e., OF_1 (i) OF_1 (i)', for each i, and similarly for OF_2 (i) and OF_3 (i). The relative effectiveness of the RCS for an experiment i is defined as

$$RE\ (i) = \frac{OF\ (i)}{OF'\ (i)} \tag{14}$$

This measure of relative effectiveness decreases as the estimation errors due to an imperfect RCS increase, and approaches 1 as the RCS approaches perfection. The vector measure of relative effectiveness has as its components the factors in equation (14):

$$RE = \left[\frac{OF\ (1)}{OF\ (1)'}, \frac{OF\ (2)}{OF\ (2)'}, \ldots, \frac{OF\ (k)}{OF\ (k)'}\right] \tag{15}$$

where, as before, the unsubscripted OF (i) and OF (i)' refer to whichever one of OF_1 (i), OF_2 (i) or OF_3 (i) is being used as the objective function.

If the different experiments can be ranked and given weights according to their importance, a single index of relative effectiveness can be obtained as

$$RE = \frac{OF}{OF'} \tag{16}$$

where OF and OF' are the weighted sums of the objective functions for the individual experiments (see equations (7), (8) and (9)).

The Estimation of Variance

In the above discussion, it was assumed that the purpose of the data collection mission was to estimate as accurately as feasible a series of physical properties whose true mean values were represented by μ_1, μ_2, ..., μ_k. Realistically, the estimation process should not be restricted to estimating mean values of the distributions, as it may be of equal importance, or conceivably more important in some instances, to estimate other moments of the distributions, e.g., the variance.

For those physical properties for which such estimates are desired, the objective functions can be modified to include other moment estimates in a similar manner to that already described. For example, suppose that for some experiment i an objective is to measure not only the mean μ_i but also the variance σ_i^2. The estimator for σ_i^2 is

$$s_i^2 = \frac{1}{n_i - 1} \sum_{i=1}^{n_i} (x_{ij} - \bar{x}_i)^2 \tag{17}$$

and any of the previous objective functions could be applied to this estimator; e.g.,

$$OF_2\ (i) = \frac{1}{\sigma_i^2}\ E\left[s_i^2 - \sigma_i^2\right] \tag{18}$$

or

$$OF_3\,(i) = E\left[(s_i^2 - {}_i^2)^2\right] \qquad (19)$$

One is still faced with the problem of giving adequate "weight" to this estimate relative to the estimate of the mean for the experiment; this problem will not be considered further here.

Effectiveness Allocation

In the allocation of effectiveness "values" to different experiments, physical characteristics concerning which the system is to gather data can be represented by statistical spatial/temporal distributions whose moments are presumed known (for the purposes of allocation). Random samples could be taken from these distributions to realistically estimate the data-gathering activities of the spacecraft segment of the system. Since the allocation must cover the system operating in a realistic environment, it is pertinent to consider possible changes in the planned experiments as data are obtained during the mission.

The first objective function, OF_1 (i), has the property that if the n_i observations x_{ij} are random samples from a normal distribution, the objective function depends only on σ_i and not on μ_i:

$$OF_1\,(i) = E\left[\bar{x}_i - \mu_i\right] = \sigma_i \sqrt{\frac{2}{\pi n_i}} \qquad (20)$$

This is not generally true for other distributions, or for other objective functions; e.g., for OF_2 (i),

$$OF_2\,(i) = \frac{1}{\mu_i} \; E\left[\bar{x}_i - \mu_i\right] \qquad (21)$$

$$= \frac{OF_1\,(i)}{\mu_i}$$

Employing OF_1 (i), if two experiments take the same time to perform each individual reading and the total time for experiments is fixed (or, equivalently, if the experiments require different unit times but the total number of experiments allowed is fixed—e.g., by other resources) the method of Lagrange multipliers can be used to determine n_1 and n_2 such that $OF_1\,(1) + OF_1\,(2)$ is minimized.[1] The result is

$$n_1 = \left(\frac{\sigma_1^{2/3}}{\sigma_1^{2/3} + \sigma_2^{2/3}}\right) n_0 \qquad (22)$$

$$n_2 = \left(\frac{\sigma_2^{2/3}}{\sigma_1^{2/3} + \sigma_2^{2/3}}\right) n_0 \qquad (22)$$

where

$$n_1 + n_2 = n_0$$

so that

$$\frac{n_1}{n_2} = \left(\frac{\sigma_1}{\sigma_2}\right)^{2/3} \qquad (23)$$

or, more simply, if we specify that $OF_1\,(1) = OF_1\,(2)$, we would have

$$\sigma_1 \sqrt{\frac{2}{\pi n_1}} = \sigma_2 \sqrt{\frac{2}{\pi n_2}}$$

or

$$\frac{n_1}{n_2} = \frac{\sigma_1^2}{\sigma_2^2} \qquad (24)$$

so that the number of samples of each would be directly proportional to their variances.

In a real data-collection mission, normally the values of μ_i and/or σ_i would be unknown, otherwise there would be no need for measurement. The initial plan for experiments can therefore be considerably in error, from the standpoint of minimizing experimental error. The effectiveness allocation should include investigation of the gains in accuracy through real-time changes in experiment plans based on early data samples.

RCS Accountable Factors

If the above effectiveness measurements are to be useful to the design of the RCS, means must be provided for measuring the relationship between $\hat{x}_i$ and the RCS accountable factors. Accountable factors are those RCS factors which are known, or suspected, to have an impact on system effectiveness.

[1] The case of different unit times and fixed total time can be treated similarly.

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Let us assume that the experiment of concern is soil mechanics and that the measure of information received is the number of samples obtained. The amount of data gathered might then be expressed as follows

$$\hat{x}_{sm} = \frac{TA_{sm}}{TS_{sm} + TB_{sm}}$$

where

$\hat{x}_{sm}$ = Number of soil mechanics samples obtained (n_i in the system notation)

TA_{sm} = Time available for soil mechanics sampling (T_k in the system notation)

TS_{sm} = Time required to obtain a sample, given that the sensor is in position

TB_{sm} = Time between samples, given that the soil mechanics experiment is in progress

In order to identify specific RCS accountable factors it is necessary to analyze the above factors individually, as follows

Let

$$TS_{sm} = NS_{sp} (TS_{sp} + TC_{sp}) (1 + PR_{sp})$$

where

NS_{sp} = Number of steps in the sampling process

TS_{sp} = Inherent time required to perform a step in the sampling process, given that a command has been received.

TC_{sp} = Time to command a step in the sampling process

PR_{sp} = Probability of step repeats caused by errors in the RCS

and

$$TB_{sm} = TS_{sm} + TR_{sm} + TRC_{sm}$$

where

TS_{sm} = Time to select the best location for the soil mechanics device

TR_{sm} = Time to reposition the soil mechanics device, given that a location has been selected.

TRC_{sm} = Time to recalibrate the soil mechanics device, if any.

In the above example the variables which appear to be RCS accountable factors are as follows

TC_{sp} The time required to command a step in the sampling process will depend upon the manner in which a series of steps is preprogrammed (if at all) and the verification procedure used to assure that a given step has been performed successfully.

PR_{sp} The probability of step repeat may again depend upon the command verification procedure as well as the capability of the RCS to correctly assess the spacecraft situation.

TS_{sm} The time to select the best location for the soil mechanics device will depend upon the time required to convert mission plan objectives into spacecraft commands and, possibly, the time required to modify the mission plan, if this is necessitated by telemetry received.

TR_{sm} The time required to reposition the sampling device will depend on the inherent speed of the repositioning device as well as the number of steps in repositioning (which may depend on situation assessment).

TRC_{sm} Recalibration, if required, will depend upon the time required to select and process the recalibration commands as well as the speed and reliability of the spacecraft state assessment following recalibration signal transmission.

Missing from the above relationships are those factors related to resource availability. That is, the success of any experiment will depend upon the availability of certain resources such as power and telemetry channels. For example, if it is found that the power consumption required to obtain the number of desired samples is in excess of that anticipated, dynamic resource reallocation would be required, possibly placing an extra load on the RCS.

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The preceding example indicates that there are two major categories of RCS accountable factors—time and reliability. Both can be subdivided further to make them directly relatable to individual function performances.

Functional Reliability. Functional reliability can be defined for this study as the probability that a given quality of an output state meets the standard for that state. When discussing an output such as command signals, one standard is that of format consistency. Formatting can be automated and is subject to a variety of quality control measures. Although the problem is not simple, it is straightforward and is amenable to solution by techniques such as the CVE proposed by JPL. Another standard is command content; i.e., the appropriateness of the signal. Compliance to the command content standard is more difficult to measure and less amenable to verification. Factors that contribute to the command signal content are:

1. Knowledge of the current state of a particular mechanism. This depends upon the amount and accuracy of the information available concerning the system. This information is obtained by combining known characteristics of the mechanism with telemetry data to allow the current state to be assessed.

2. Knowledge of a desired state predicated upon the knowledge of both the current situation and a "next step" plan to achieve some ultimate objective. Generally, when the existing state and the desired states are compared, the difference provides the proper cue for corrective action.

   In some instances, e.g., contingencies, the course of action to be taken is not a simple nulling of the error signal derived by comparing existing and desired states. Normal procedures and expected contingencies should be provided for; i.e., a plan made available to revise an intermediate objective, to alter the technique to accomplish a given objective, or to provide insight in reallocating available resources to other objectives.

3. Selection of the control signals that enable the determined course of action to be accomplished. These signals are generally obtained by mating specific commands to specific desired steps and sequences. The length of the sequence is dependent upon:

   a. The confidence in the assessment of the situation;

   b. The confidence in the course of action selected;

   c. The predicability of the response of the mechanism to the commands to be given.

It cannot be assumed that reliability may be sacrificed in favor of time. This trade-off is a function of the subsystem, mechanism, or sensor under control; the situation in which control is being effected; and the effect of an error made during control. It does not lend itself to cursory examination.

A factor which must be considered in establishing standards for command reliability is the manner in which an error affects the mechanism being controlled. The rate of degradation as a result of incorrect commands bears upon the criticality of the error. The time to note and correct the error prior to damage is thus a function of the degradation rate and the time delays in the control loop. In general, all other characteristics being equal, the longer the delay time imposed on the system, the greater the reliability requirement.

Since correct command content is so important, it is expected that certain quality control measures will be required. Current practice within the DSN involves quality control through parity check, interlock, confirmation of command validity, verification of receipt of command at each deep space instrumentation facility, and confirmation of receipt of command at the spacecraft. Quality control per se is not a constraint; however, established techniques or practices may be. The ways in which quality can be achieved are many, consisting of repeated performances, parallel performances, comparisons of output, etc. The goal is to achieve a high quality while expending a minimum of resources.

The costs of achieving high reliability in terms of time and equipment should be traded off against the costs of mission failure due to an inadequacy of quality control measures. Usually, the trade-off favors high quality-control measures unless the time associated prevents effective quality control. To resolve this problem optimally, one must consider the time required to achieve a certain reliability, the effect of increasing time delays, the effect of errors on different spacecraft subsystems, and the physical costs of the quality-control means.

A quotation of reliability alone is usually considered insufficient to specify the probability of success. A confidence value used in conjunction with reliability may denote different connotations to the reader, such as variance, sample size, etc. Here confidence is used to indicate a measure of the expectancy that the achieved reliability values will coincide with the quoted values.

Techniques to attain high performance confidences within the Remote Control Station are as follows:

1. Adoption of a series or parallel performance approach.
2. Use of experienced personnel (including highly-skilled and trained personnel) and proven automatic equipment.
3. Use of prediction techniques such as simulation.
4. Pre-mission exercises to check personnel, procedures, and equipment.

Response Time. Response time is normally considered to be the time required to execute an action, given a cue. This definition is also valid when speaking of the RCS. When considering the total control loop, however, it is convenient to consider response time as comprised of the following times:

1. Detection Time
   a. The time required to receive the signal from the space vehicle; plus
   b. The time to process the signal and present it within the RCS; plus
   c. The time to detect the existence of a particular state A.
2. Decision Time

   The time required to associate the correct state B with the detected state A.
3. Actuation Time
   a. The time to actuate control once state B has been identified; plus
   b. The time required to obtain the command to effect state B; plus
   c. The time to process the command to a form compatible with transmission; plus
   d. The time required, due to distance, for the signal to reach the space vehicle; plus
   e. The response time of the space vehicle.

Regardless of the source of the time delay, the effects are the same. That time associated with distance is fixed, whereas the remaining time delays are a function of the capability of the ground-support equipment and processes. Those times that are subject to variation within the RCS are accountable factors for effectiveness.

When time is treated as an accountable factor, the division of the time continuum into real time, near-real time, and non-real time categories no longer becomes useful. The critical factor is the allowable time between the occurrence of event A (the initiating state) and the change to event B (the output state). The allowable delay could be as short as a few seconds or as long as many days. In any event, any performance deficiencies which contribute towards the possibility of not accounting for event B within the time required has potentially detrimental effects on system effectiveness. On the other hand, delays in response which will not exceed the allowable delay time will not have any significant effect on the overall system performance. For purposes of discussion, the term "real time" will still be used to mean those cases where the allowable delay is quite short and the consequences of effecting the delay will have a significant impact on degrading overall system performance. The specific time period for this allowable delay cannot be specified since it depends on event A, event B, and the consequences of not achieving event B.

QUANTITATIVE ANALYSIS REQUIREMENTS

Usually the overall objective of a system design effort is to obtain the "optimum design." Quite often, however, the term optimum is never clearly defined. An optimum system may be one which provides the maximum effectiveness for a given cost or the minimum cost for a specified level of effectiveness, or, costs removed, the maximum effectiveness within some time period. The point is, whenever one desires an optimum design, the definition of optimum must be stated. For example, the RCS optimization criteria might be stated as follows:

> Achieve the maximum effectiveness for a given cost and within a given time period.

Assuming that effectiveness can in fact be defined and optimized, there are three major implications contained within the stated objective. These are: (1) whatever the achieved optimum effectiveness is, it is worth the predetermined cost; (2) design completion after to the preestablished completion date is of no value; and (3) gains in effectiveness obtained after the required completion date are valued less than the loss in time. Although it is possible that these relative values can be established a priori, it is more likely that they will not be.

If one broadens the constraints of time and cost, it is then possible to derive a set of possible system solutions from which a selection can be made. For example, consider the figure below.

In this example, effectiveness is plotted against cost <u>and</u> time. If effectiveness were maximized for every cost/time combination within the constrained volume, the result would be a solution surface. It would then be possible to select any point on the surface and design the associated system, thus providing a certain degree of latitude to the final decision-making process.

In a system such as the RCS which is to be integrated into a supersystem which is, to a large extent, already in existence, the constraints on the optimization process are more complex than time and cost. Examples of such constraints, in addition to time and cost, are (1) existing equipment which must be used for certain functions, and (2) the size of the structure within which the RCS must be housed.

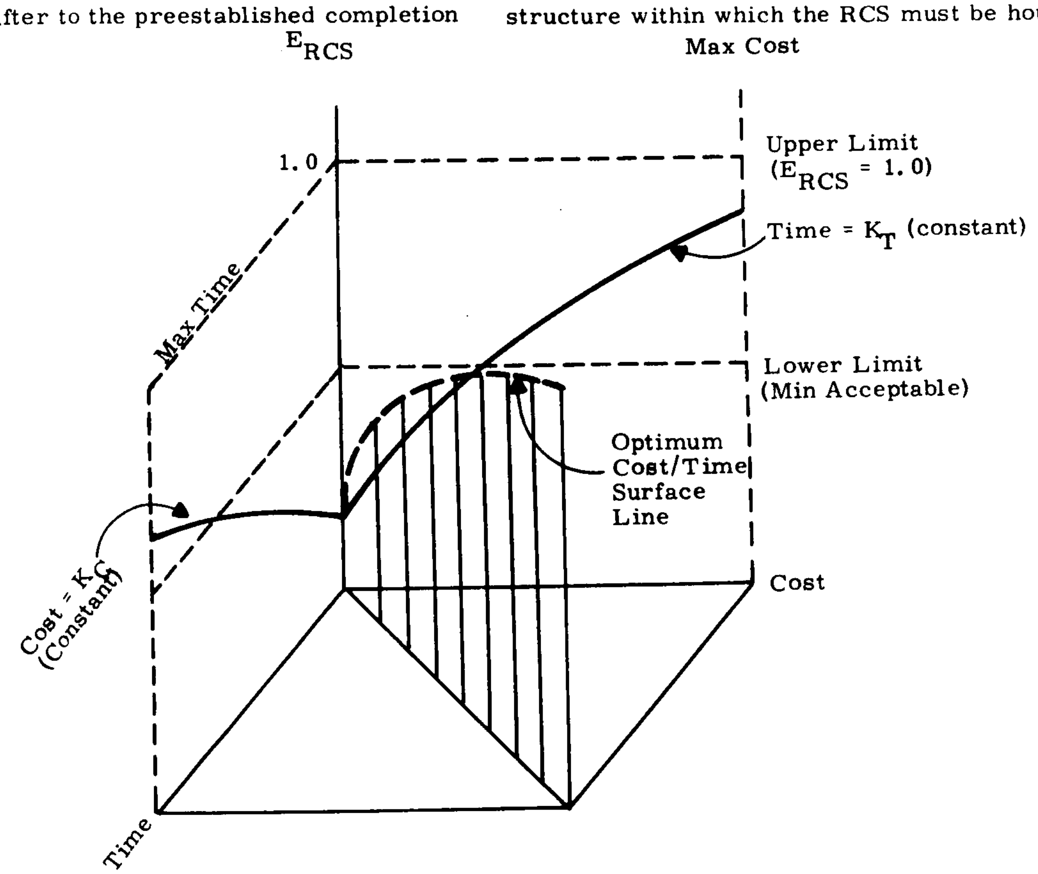

Figure 2-17. A sample solution surface for optimizing system design.

To approach the "optimum" design, it will be necessary to express requirements in quantitative terms at varying levels of detail. The designer must have information on the quantitative relationship between the accountable factors and system effectiveness if he is to identify points on the solution surface. The requirements presented in the previous sections are stated only in qualitative terms. These qualitative requirements are a necessary intermediate product for design conceptualization, but they are not sufficient for final design. For one thing, the lack of quantitative requirements will force the designers to bank heavily on logical derivations and engineering judgments, without any means of assessing the adequacy of either the derivations or the judgments. On the other hand, the qualitative requirements are considered sufficient to allow development of a conceptual design, the adequacy of which can be assessed if and when the qualitative requirements are transformed into quantitative terms.

Because of the number of variables involved in the definition of the optimum RCS, it appears that means must be provided to compute system effectiveness and the means must be flexible enough to incorporate design constraints and provide a relationship between effectiveness and cost and time so that a proper trade-off analysis can be made at higher levels. Besides these criteria, the means must also be capable of evaluating alternate functional or physical design concepts in terms of effectiveness, and handling either a generic or specific spacecraft as required.

In order to implement the means for computing system effectiveness and for establishing relationships between system-effectiveness criteria measures and accountable factors, certain basic quantitative data will be required. These quantitative data were not derived during the study since the term of the contract did not permit this effort. Any subsequent efforts to translate the qualitative requirements to quantitative terms will require, at a minimum, the types of quantitative data described below.

1. Data on the distribution of demands placed upon the RCS and the manner in which the demands affect the major RCS functions. It is anticipated that demands will be a function of the planet under observation, mission type, domain of investigation, and spacecraft mechanism types. It will not be possible to obtain specific quantitative data on all factors in the very near future. However, it should be possible to construct a generic set of missions expected to place a high demand load on the RCS.

2. Time allowances for individual sets of experiments which are reasonable with respect to the mission of item 1.

3. Allowable time delays for categories of spacecraft states, considering a generic set of spacecraft mechanisms over the full range of mechanisms requiring short and long response times.

4. Allowable success probabilities with respect to achieving a given ratio of $\frac{\hat{x}_i}{x_i}$.

5. Reasonable estimates of time in functions for various types of performances within major RCS functions.

AN APPROACH TO QUANTITATIVE ANALYSIS

Subsequent to definition of the system-effectiveness criteria measures and the accountable factors, some tool for relating the two sets is required. The tool must be sufficiently flexible to allow one to establish the relationships under a variety of system conditions. The tool should be essentially a dynamic synthesis means wherein synthesis is defined as the process of combining entities within a system (functions in this case) to form a set. The combining process should allow measurement of not only the total set or system, but also the extent to which the parts contribute to the set or system.

In another sense dynamic synthesis is the process of relating dependent variables to independent variables. Systems analysts term these dependent variables "measures of effectiveness," whereas independent variables are referred to as "accountable factors," or those factors which are known or suspected to impact system effectiveness. Ideally, the means used for dynamic synthesis can be used to optimize the dependent variable; however, this is possible only where the relationships are "well-behaved." In the case of the RCS, severe interactions appear to rule out optimization techniques such as linear, nonlinear or dynamic programming. In fact, the underlying logical nature of real-time spacecraft control has resulted in the conclusion that digital simulation offers the best approach to dynamic system synthesis even though direct optimization is not possible with this approach. The details of the recommended simulation approach are discussed in this section.

DIGITAL SIMULATION MODEL DESIGN APPROACH

Digital simulation is basically a numerical technique for conducting experiments on certain types of mathematical and logical models describing the behavior of a system on a digital computer over periods of real time.

The ground rules upon which the basic design concept of the RCS model was based are as follows:

1. Model scope shall include spacecraft and DSN functions so as to allow estimation of total system effectiveness.
2. Concentration shall be on real-time control; however, the model shall have the capability of handling all types of control.
3. Model structure should accommodate analysis of any anticipated RCS/spacecraft systems with only minor modifications.
4. Accountable factors shall include, but not be limited to, function performance time, functional reliability, function decision-making capability, and resource availability.

As mentioned above, digital simulation is a technique for conducting experiments on a system model over periods of real time. Examples of questions which such experimentation is expected to answer are as follows:

1. Given a proposed set of means for performing RCS functions, what is system effectiveness?
2. How do two different proposed approaches differ in terms of system effectiveness?
3. To what functions, or accountable factors, is the system more sensitive?

BASIC SIMULATION STRUCTURE

The simulation model of the RCS would be comprised of a set of computer subroutines, one for each of the RCS functions, linked together by a master control program which manages the operation of the simulation. The recommended simulation technique is of the imminent event, Monte Carlo, transaction type. In this approach, information and commands "flow" through the model functions in the form of transactions. For example, a transaction would be generated by the master control program whenever a mission phase is to be initiated. This transaction would then be sent to the Mission Planning (f) function to determine if the mission segment may, in fact, proceed on schedule. If there is no conflict, the transaction would move to the Assess/Determine Course of Action (2/3) function for the selection of a course of action. Depending on the detailed design of the simulation, the latter function may generate new transactions for each step within the mission segment, or it may use the original transaction as the "carrier" of the step information. Upon completion of a mission phase, all associated unnecessary transactions would be erased.

The purpose of the transaction is to trigger the execution of functions. Once a transaction enters a function, its next function and time to leave the current function are determined. In addition, any other computations and/or decisions are made and the results recorded, either in the transaction itself or in some other table.

Although the master control moves through time in discrete steps, the imminent event nature of the recommended approach allows these steps to be as small as 1×10^{-12} seconds or as large as 1×10^{12} years within the same simulation run. For example, if a transaction represents the occurrence of a discrete telemetry signal, it would be possible to simulate time delays as small as those occurring between Goldstone and the RCS, although such a necessity is not anticipated.

As mentioned above, the simulation structure is also known as a Monte Carlo type. Simply stated, Monte Carlo is a technique used to obtain pseudorandom samples from a known frequency distribution. For example, if the time in a given function is normally distributed and the mean and variance are entered as data, the time for a given activity would be determined by solving the inverse cumulative distribution function (or an approximation thereof) using a uniform pseudorandom deviate as the independent variable.

Although many of the calculations within the simulation will use the probabilistic Monte Carlo technique, others will be deterministic, such as diurnal cycle and ephemeris calculations.

MODEL INPUT

Model input data must reflect the best estimation of the performance capabilities of the means being evaluated. In certain cases, however, accurate data are not immediately available necessitating a parametric investigation of the range of interest. Regardless of the means of data acquisition, the model must be capable of handling variables at a level of specificity consistent with the types of decisions which it is designed to support. Examples of this type of input are as follows:

1. Function performance time:—Performance time must be provided for each model function. If this time is expected to be subject to random variations, the underlying frequency distribution and the necessary moments (e.g., mean and variance) must be provided. Also, if the performance time varies with other model variables the relationship should be provided.

2. Function resource requirements:—The performance of a given model function will be contingent upon the availability of a set of prescribed resources. Examples of such resources are:

   a. Personnel by type and quantity;
   b. Telecommunications channels;
   c. Spacecraft power;
   d. RCS control and display consoles.

3. Spacecraft performance characteristics:—The spacecraft configuration used in the model will be a generic structure which may be made specific by establishing certain parametric values. Examples of these are:

   a. Number of spacecraft functions;
   b. Number of subsystems;
   c. Power consumption by subsystem;
   d. Constraints on simultaneous performance;
   e. Subsystem response and performance time.

(It should be noted that other spacecraft characteristics are inherent in the mission plan.)

4. Hardware reliability:—The extent to which reliability should be included in the model is not well-established. However, models of this type are well-suited for evaluating reliability effects. Depending on desired complexity, the model could be designed to include the following factors.

   a. Spacecraft reliability:—Since unmanned spacecraft failures are not normally repairable, failure rate data must be accompanied by a failure mode and effects analysis, such as available redundancies under the control of the RCS and changes in spacecraft performance characteristics.

   b. RCS hardware reliability:—Hardware failures can increase time delays because the necessary systems are not available. Undetected failures can also degrade the effectiveness of the RCS to properly control the spacecraft. Therefore, RCS hardware reliability, malfunction detection characteristics and repair time may represent important factors in the consideration of alternative means approaches.

5. Human reliability:—Human reliability could be expressed in terms of probability of correct function performance. However, this would not be sufficient as model data since the effects of errors must also be known. Errors which are detected within the RCS would tend to increase the time delay, whereas undetected errors would tend to decrease effectiveness through unsafe or inefficient spacecraft operation. Therefore, if human reliability factors are to be included in the model, error effects must also appear.

6. Mission plan:—The mission plan would represent the primary impetus for model operation. The plan should cover the entire mission and should include the following:

a. Start/stop time of each sequence;
b. Sequence objectives, if known in advance;
c. Sequence objective criteria if objectives are to be identified during experimentation;
d. The means by which spacecraft resources are to be reallocated in the event of a contingency situation.

MODEL OUTPUT

As the simulation progresses, data will be gathered on the performance of the system. One of the primary statistics to be collected will be the amount of information gathered by the spacecraft, such as the system-effectiveness measures discussed earlier. Other outputs would be:

1. Mean and variance of total system delay time attributable to the RCS.

2. Delay time breakdown within the RCS contributed by each function, queues for functional resources, and errors.

3. Percent of resource utilization including time variations (i.e., peak loads) by resource type (man, display, computer, etc.).

4. The number of erroneous commands transmitted to the spacecraft.

5. The number and length of delays caused by equipment failure.

POTENTIAL MODEL USES

The nominal value of system effectiveness can be obtained by assuming:

1. An RCS functional configuration.
2. A given spacecraft system.
3. A specific mission plan.

The impact of varying each of the preceding factors as inputs to the model will result in a variation of RCS effectiveness. A selected set of RCS means can be added to assess the conceptual design presented in chapter III. The variations on the spacecraft system and the mission plan will be bounded by the performance characteristics of a generic spacecraft and the data-collection objectives identified by the analysis presented in earlier sections. A limited number of runs is expected to establish the sensitivity of the RCS effectiveness to these variations. A greater number of runs is expected to determine the effect of varying the compositional and physical characteristics of the RCS.

Data-Collection Effectiveness and RCS Performance Time

During the discussion on system effectiveness, a simple example based on the soil mechanics experiment was used to show how RCS function performance time affected achievement of data-collection objectives. The simulation model provides a more realistic and accurate means of deriving this relationship, not only for a single experiment but for all experiments and functions aboard the spacecraft.

Since the model is not a closed-form optimization technique the analysis must begin with some nominal "system" which is comprised of function performance-time estimates based on a selected set of RCS means and/or the basic functional requirements with "reasonable" time estimates. Some of the questions which might be asked regarding the nominal system are:

1. What are the effects of varying overall RCS performance time?

2. What are the effects of varying performance time at a given RCS hierarchical level?

3. What is the contribution of an individual function to total performance time?

4. What are the effects of spacecraft performance characteristics on the nominal RCS system?

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One way of answering these questions is to perform a parametric analysis of these variables. For example, it should be possible to develop quantitative relationships such as those illustrated below.

into three major groups. They should be associated with the issuing commands and the resultant reliability values required for satisfactory spacecraft performance. The effects of errors in command content

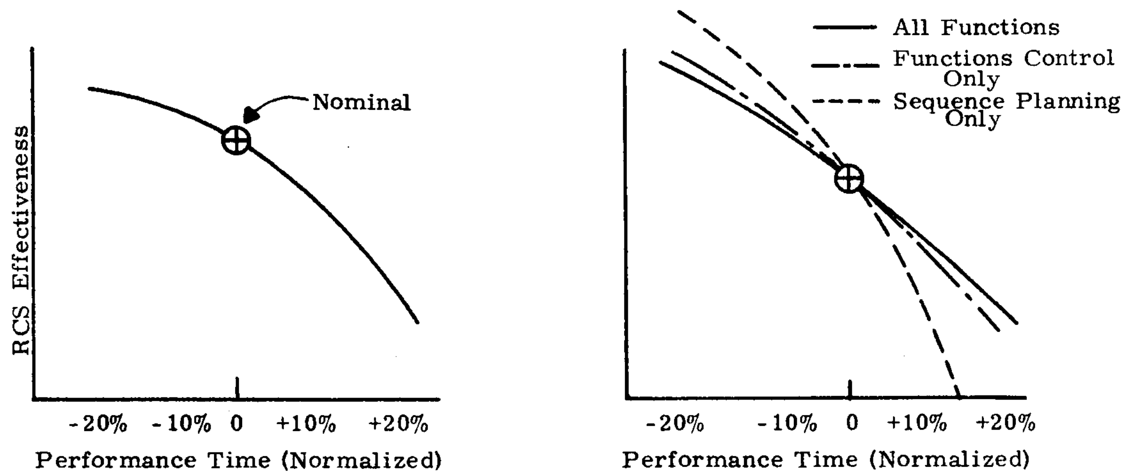

Figure 2-18. Variation in RCS performance time vs. RCS effectiveness.

<u>Data-Collection Effectiveness and RCS Performance Reliability</u>

The reliability of performing the functions within the remote control station is a factor contributing to the measure of RCS effectiveness. To ascertain the effect of varying levels of reliability, the following questions could be examined.

1. What is the effect of varying the reliability of functional performance?

2. What is the effect of varying the reliability of performance for different state classes (e.g., types I, II and III)?

3. What is the effect of varying the reliability of the performance means, including man, within the functions identified as sensitive to reliability variations?

The effect of errors on the data-collection objectives in terms of spacecraft system response characteristics should be identified. This identification must result from an analysis of the individual steps, the acceptability of the spacecraft to erroneous commands, and the effect of an erroneous command if accepted. In this regard, it is felt that the effects of erroneous commands can be classified

or format are classed as:

1. Critical

   a. Effect is irreversible and can significantly affect mission performance.

   b. Effects may adversely impact other operational capabilities.

   c. Effects cannot be predicted.

2. Normal

   a. Normal cognizance of effects can prompt corrective action prior to damage or data loss.

   b. Effects can be reversed if considered abnormal.

3. Fail-safe

   Effect cannot adversely affect mission.

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The variations of reliability and their effect on RCS effectiveness may be illustrated graphically by relating the increase/decrease in effectiveness to the reliability variation in the following manner.

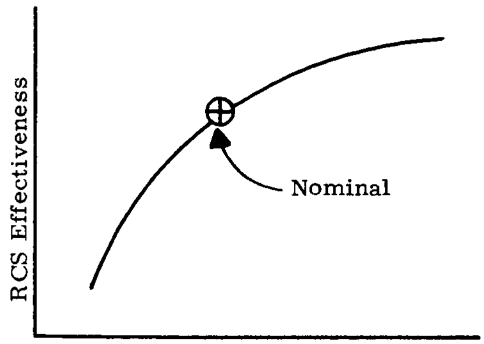

Figure 2-19. Variation in RCS performance reliability vs. RCS effectiveness.

Data-Collection Effectiveness and Spacecraft Characteristics

As mentioned earlier, input data for the nominal RCS should be developed assuming a selected spacecraft. Therefore, in order to evaluate the impact of a variety of spacecraft, it will be necessary to modify the input data in accordance with different spacecraft performance characteristics. Examples of such data modification could be as follows:

1. Number of RCS control functions;
2. Performance time within each function;
3. Resources (men, computers, displays).

Once this is accomplished, the parametric analysis described above could be repeated using the new nominal system.

The functional requirements for the control of a generalized unmanned spacecraft were developed in chapter II. The implementation of these requirements necessitates a control complex. It was assumed that this complex, the Remote Control Station (RCS), is to be situated within the Jet Propulsion Laboratory's Space Flight Operations Facility (SFOF). The conceptual design for the RCS presented in this chapter considers the spacecraft requirements, the RCS functions required to control the spacecraft, the informational needs of the identified functions, and an organizational structure within which effective control can be exercised.

The ultimate design of the RCS should contain, at a minimum, the following information if it is to be implemented:

1. A functional configuration of the system, including input/output states, the input source, and output destination of the information and/or physical effects which comprise these states.

2. A communication network and logic which transfers informational states between functions.

3. The functional means required to achieve function output requirements.

4. The physical means required to perform the functional means, such as physical layout, communication means, presentation means, and computation means. Physical means should be described at a level of specificity sufficient to allow acquisition of fabrication of actual hardware or software.

The RCS functional requirements presented in the previous chapter are necessary, but not sufficient, to arrive at final design. The purpose of this chapter is to develop a design concept and indicate the processes required to produce an implementable final design from such a concept. This chapter also points out the need for quantitative data prior to final design of the Remote Control Station.

OPERATIONAL CONCEPT

The design of a system is generally predicated upon a preliminary concept of how the system is to operate. This notion is referred to as an operational concept. It is the result of investigations into the objective of the system, the environment in which the system must operate, and the constraints which bound the system in scope, cost, and complexity. Operational concepts are not intended to constrain design efforts, but should provide the basis for iterative design conceptualization. Such an operational concept was developed from the results of analyses conducted in the early phases of this study. The baseline operational concept for the Remote Control Station described in the following paragraphs was developed assuming that the spacecraft configuration consisted of the following subsystems. The control requirements for these or similar spacecraft subsystems, were developed and are described in detail in tables 2-11 through 2-17 in chapter II.

1. Experiments
   a. Fixed, requiring switching only
   b. Deployable, requiring positioning
   c. Television
2. Information-Transfer system
3. Antenna-Positioning System
4. Auxiliary-Power System
5. Steerable Solar-Energy Collection System
6. Environmental-Control System
7. Locomotion System
8. Experiment-Positioning System

It was determined that all spacecraft functions support the experimental objectives. This is shown diagrammatically in figure 3-1 where a state change of one or more supportive systems is required to support an experimental objective. For example, assume that the mission plan calls for a change of state of an experimental subsystem, identified as "Experiment State Change" on the diagram. The state change may require that commands be issued to a specific experimental subsystem; namely, a TV, a deployable, or a nondeployable experiment. When the experimental subsystem is of the deployable

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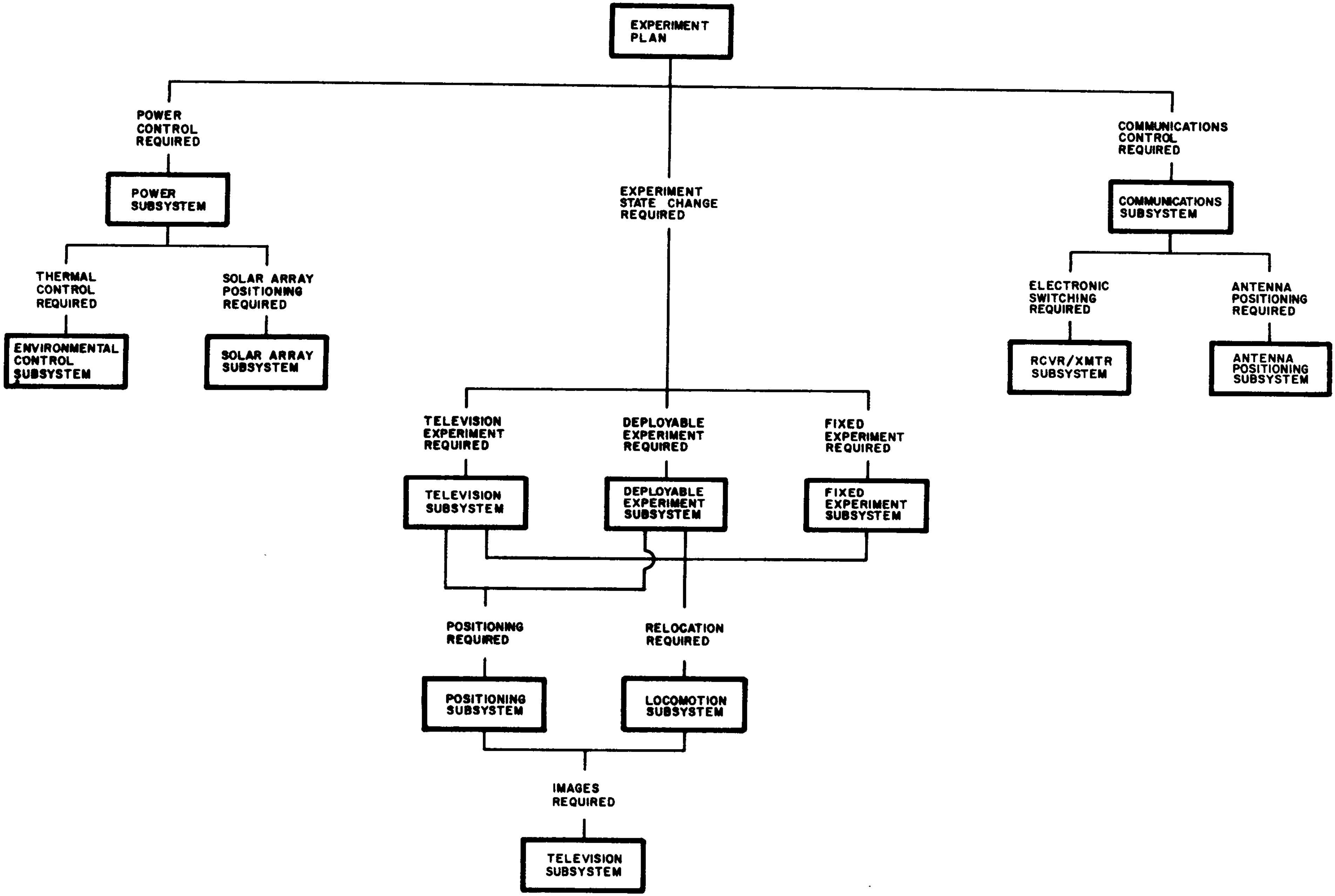

FIGURE 3-1 DEPENDENCY OF S/C SUPPORT FUNCTIONS UPON DATA COLLECTION OBJECTIVE

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class, changes in position are likely to be required. Such changes usually necessitate that the TV subsystem be used in a supportive role. This is also true when relocation is required. Each state change, direct experimental or supportive, requires that the communications and power subsystems be utilized.

The supportive systems provide the proper position, location, environment, power and telecommunication states necessary to achieve the experimental state changes that are desired. In the case of a fixed spacecraft, the supportive-system state changes can be predicted as a function of the experimental objectives. All telecommunications state changes (in the absence of contingencies) can be slaved to the transmission or reception requirements. These requirements are established by the experimental objective or a supportive-system requirement necessary to achieve the objective. The steering of a high-gain antenna is a predictable task[1] with or without any external requirements. The telecommunications system can thus be automatically controlled by slaving it to the experiment state changes.

In a like manner, the environmental control of sensors and spacecraft compartments is subject to control by responding to the changing specifications on desired temperature. As temperature is monitored, it may be stabilized by automatically heating or thermal switching. A relatively simple automated routine can perform this task.

The power system control can be effected automatically as various demands are made upon that resource. The routine that may provide the control should be designed to inhibit excessive loads on the power supply, both in magnitude and duration. The loading priorities may be a part of this routine, or this information may be supplied as an input by an operator. The positioning of the solar array is quite simple, from cues supplied by power input, by solar sensors, or by astronomical computations. The interval between positioning actions depends upon the rate of power expenditure, the rate at which recharging can be accomplished at various array positions, and the magnitude of the pointing angle changes as a function of time. Different missions or mission phases, e.g., orbital planetary spacecraft, may require spacecraft closed-loop control, while stationary lunar spacecraft solar arrays can be positioned via ground control from Earth.

Experimental objectives requiring changes in position (TV and other sensors) fall into two categories or modes. The first can be preplanned and executed in whole or part by previously prepared sequences. This implies automatic control primarily, since the manual activities were conducted prior to the time control was required, and control is executed by reading out preprogrammed command sequences. This technique has been efficiently used, particularly on SURVEYOR I in the television experiments. It can be used for any sequence of events provided:

1. The operation lends itself to serial action.
2. The actions can be predicted in magnitude and polarity.
3. The sequence, once initiated, can be interrupted and commands inserted from an on-line command initiation device.

Other examples can be handled in a similar manner. Sensor placement can be preplanned, in many instances, and executed by preprogrammed sequences.

The second category requires that the specific action be based upon conditions or events that are not predictable. Examples of such conditions are unknown terrain features, unpredictable interactions between a mechanism and the environment, contingencies due to malfunctions, and the unpredictability of certain natural phenomena (such as a meteoroid impact or lunar quake). These conditions imply that positioning of sensors must be subject to real-time (short response time) control, if only for a limited time or extent. This control is assumed to involve personnel, particularly in dtermining what to do.

Location changes result from expedient or preplanned experimental objectives. Execution of location changes, roving or locomotion, also requires real-time manual control since the conditions that prevent total automatic control of positioning mechanisms also prevent effective location control without a manual control system. Since locomotion is dependent upon sensing the conditions

[1] For a stationary vehicle. At planetary distances this task will probably be automated by closed-loop control at the spacecraft; if a lunar roving vehicle, this task will probably be controlled from the ground prior to data transmission.

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ahead (generally obtained via television) the control of this system must be considered as a necessary condition to maneuvering. This is usually true of position control when manual intervention is required.

Solar-array positioning (if this type of power supply system is used) can be accomplished intermittently by manual control or by automatic command generation based upon the existing solar-array pointing angles, the spacecraft attitude, output of a solar sensor or voltage into the storage cells, and ephemeral data. It is anticipated that periodic recharging will be accomplished as the vehicle stops to take panoramic photography or while collecting other data requiring a stop. During motion it is assumed that the solar deck would be positioned to optimize power input regardless of attitude or bearing. Thus, the horizontal position is indicated during motion, and a position near perpendicular to the solar flux while stationary.

It was noted that the experimental objectives define the total state changes to be effected within the spacecraft; i.e., all control actions originate from the desire to collect data. The systems comprising the spacecraft are designed to operate via ground command to maintain or change the conditions necessary to that goal. As a result, the data objectives initiate the sequence of events with the control station.

RCS FUNCTIONAL RESPONSIBILITIES

The functions considered to be the responsibility of the RCS are shown on figure 3-2. This figure is a repeat of figure 2-16 in chapter II. These functions, as well as others considered to be mission independent and, therefore, may be accomplished by the DSN in a supportive role, were shown on figure 2-14, also in chapter II. The functions denoted on figure 3-2 represent the scope of the Remote Control Station.

The interfaces between the RCS and other systems occur within the SFOF. Primary interfaces occur with the data-processing system, the command verification and transfer system, project management, and the existing analysis centers. The interface at the DPS is basically software. Those interfaces occuring within the command verification and transfer system are the insertion of the command sequence into the Ground Communications System for transfer to the DSIF, confirmation that the correct sequence was received, and notification from the RCS to the DSIF of time of execution (TOE). It is assumed that project management provides, authorizes, and coordinates the required supportive services of the Deep Space Net for the Remote Control Station. An interface, therefore, exists between project management and the mission control or spaceflight operations function.

The interfaces between the analysis and control functions are even more subtle, since the same personnel may perform both functions. The control and analytic functions may also involve identical display equipment. Common use of means involves a functional interface as well as an organizational one. When multiple uses are made of the same means, the priority should be given to the control requirements. This should not pose a conflict since, in most cases, the same personnel that are to provide control also provide analysis.

The major RCS functions were diagrammed for each major spacecraft state class in figure 3-3. The pertinent information required to accomplish each control function for each spacecraft function is shown as an input. This figure is similar to figure 2-15 in chapter II except an initial man-machine allocation is reflected by the shadings. This figure is essence illustrates a control configuration where each spacecraft function is treated separately. Such a configuration lends itself to systematic analysis, but may require considerable redundancy of control/display means. This figure also illustrates that a significant amount of data must be communicated to other control functions.

This communication requirement is further illustrated in figure 3-4 wherein a matrix of the two primary RCS functions was developed for each spacecraft function. It may be seen that prior to completing a function listed as "RCS Function Under Performance," information is required from those functions denoted as "RCS Function Previously Completed." A cell entry denotes these communication interfaces. Certain conclusions can be drawn from this matrix. For example, the "Determine Course of Action, Information Transfer Control" function is found to be contingent upon each desired state change; therefore, this function requires two

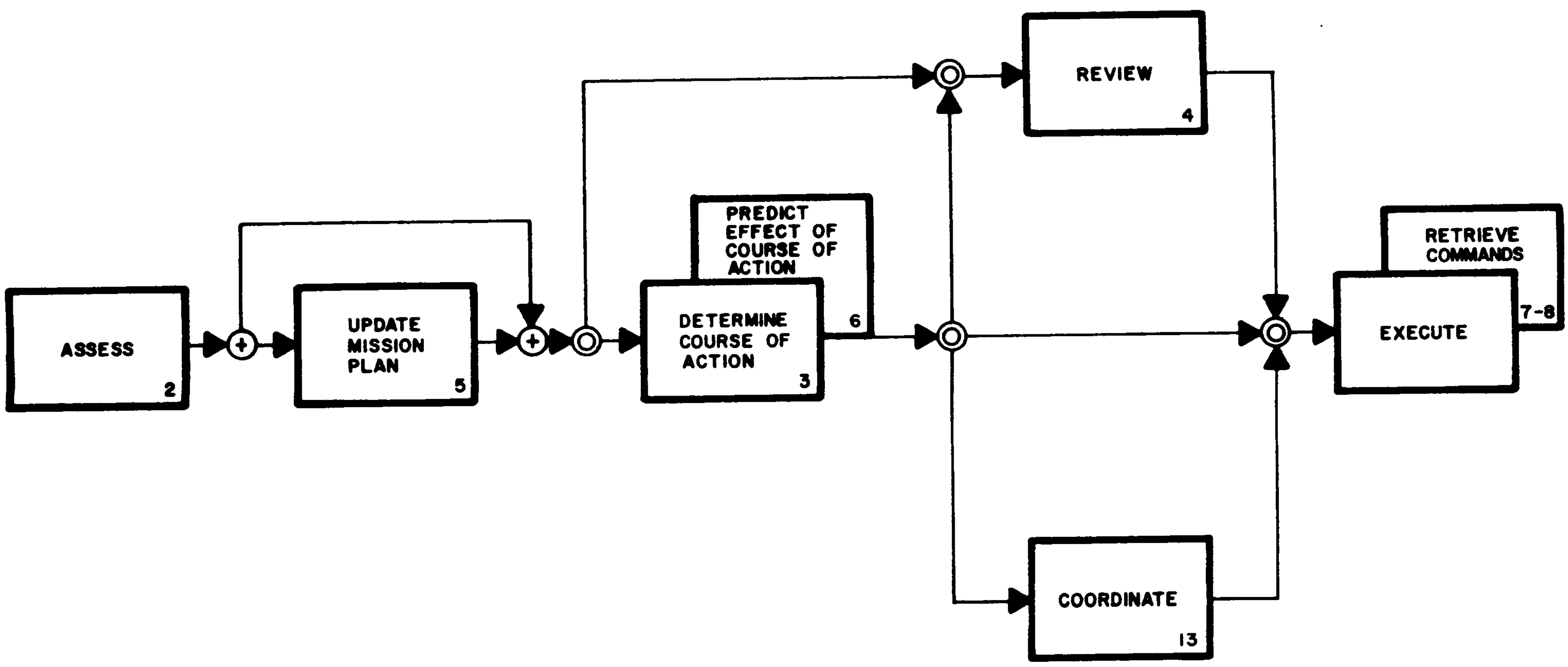

FIGURE 3-2 FUNCTIONS TREATED AS RESPONSIBILITY OF RCS

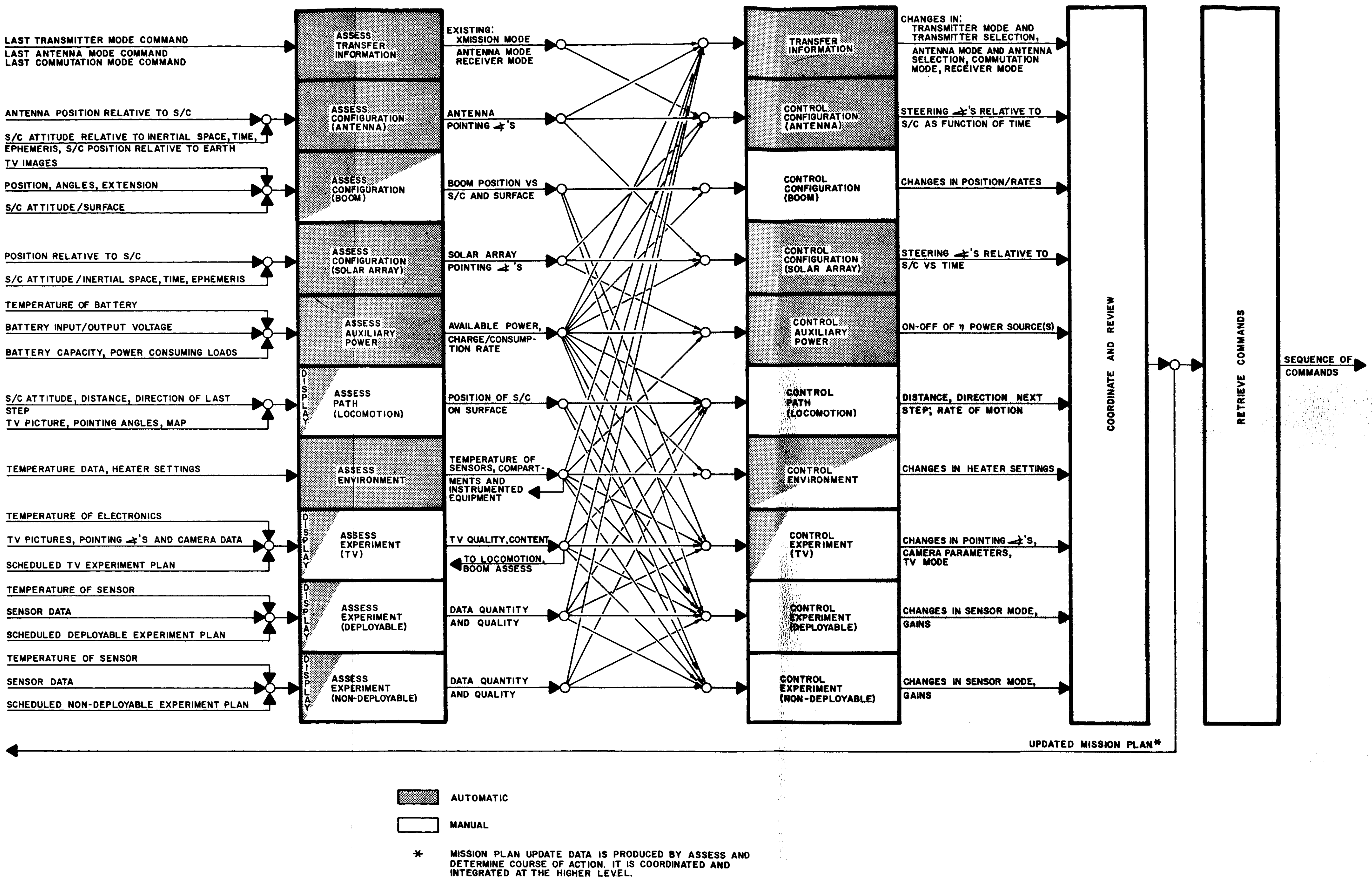

FIGURE 3-3 RCS FUNCTIONS INFORMATIONAL REQUIREMENTS

Fold out FRAME I

Fold out FRAME II

RCS FUNCTION UNDER PERFORMANCE / RCS FUNCTION PREVIOUSLY COMPLETED		ASSESS									DETERMINE COURSE OF ACTION								
		INFO. TRANSFER	ANTENNA POSITION	AUXILIARY POWER	SOLAR ARRAY POSITION	ENVIRONMENT	SENSOR	EXPERIMENT POSITION	LOCATION	TELEVISION	INFO. TRANSFER	ANTENNA POSITION	AUXILIARY POWER	SOLAR ARRAY CONTROL	ENVIRONMENT CONTROL	SENSOR CONTROL	EXPERIMENT POSITION	LOCATION CONTROL	TELEVISION CONTROL
ASSESS	INFO. TRANSFER	●	●	●		●	●												
	ANTENNA POSITION		●																
	AUXILIARY POWER			●		●													
	SOLAR ARRAY POSITION				●														
	ENVIRONMENT					●													
	SENSOR					●	●	●	●										
	EXPERIMENT POSITION							●		●									
	LOCATION								●	●									
	TELEVISION	●				●				●									
DETERMINE COURSE OF ACTION	INFO. TRANSFER CONTROL	●									●	●	●	●	●	●	●	●	●
	ANTENNA POSITION CONTROL		●		●						●	●							
	AUXILIARY POWER CONTROL			●							●		●						
	SOLAR ARRAY CONTROL		●	●	●									●					
	ENVIRONMENT CONTROL			●		●									●	●			●
	SENSOR CONTROL			●		●	●									●			
	EXPER. POSITION CONTROL			●			●	●		●						●	●		
	LOCATION CONTROL			●			●		●	●						●		●	
	TELEVISION CONTROL			●						●						●	●	●	●

FIGURE 3-4. REQUIRED COMMUNICATION BETWEEN RCS FUNCTIONS

types of information, (1) knowledge of the existing state of the Information Transfer Subsystem, and (2) receipt of a particular change of state requirement to other spacecraft subsystems. This indicates that control of the Information Transfer can be automated with other subsystem commands serving as the initiating signal. This is a type I command situation.

Antenna Position Control is dependent upon the spacecraft attitude and whether the steerable antenna is required. The former information is derived from telemetry, while the latter entails reviewing the course of action of the Information Transfer Subsystem. Commands for antenna steering on a stationary spacecraft are type I; whereas, a mobile spacecraft probably involves type II command capability from the RCS.

Auxiliary Power Control should encompass the environmental control of the spacecraft (with the exception of the thermal control of individual data-collection sensors). Knowledge of the existing loads, the proposed changes in power consumption, overload values, acceptable simultaneous spacecraft activities, thermal constraints and tolerances, and telemetry data on power input and output values and on the temperature of the spacecraft components permit Auxiliary Power Control to be implemented automatically. The resultant command-generation activity is considered to be type II control except in contingency situations where analysis and manual intervention may be required to correct a malfunction.

The Sensor Control functions are involved basically with analysis of received data and directing supportive subsystem operations to acquire additional or higher quality data. Specific sensor-oriented commands are relatively simple and rarely require reconfiguring[1] of the spacecraft to accept them. The decision-making processes preparatory to the direction of support activities preclude total automation of the Sensor Control function. The control type applicable to Sensor Control is type II.

The Experiment Position and Spacecraft Location Control functions require direction from the Sensor Control function in terms of when and where—but not how—information. In addition to directive information, the positioning and controlling functions require spacecraft status information and topographic data to complete their function. The spacecraft status information, together with the desired course of action, permits automated devices to be used in maintaining and altering the spacecraft configuration as required to achieve position and location changes of state. The commands associated with preparing or maintaining a particular spacecraft configuration are type II commands; those concerned with the actual motion are type III commands.

Both position and location control require support from the Television Subsystem. Control of the television subsystem entails both type II and type III commands. The supportive commands involving the power, information transfer, and environmental control subsystem are indicative of a class of commands that are amenable to automatic control.

Certain groupings of the controlling elements within the RCS are suggested from this analysis. These groupings, by spacecraft system or function, are illustrated in figure 3-5 in terms of an organizational structure. The organization is structured into two major control groups; one designated as being responsible for experiment-oriented activities, and the other responsible for the spacecraft-oriented activities. They are thus similar to the existing Spacecraft Performance Analysis and the Space Sciences Analysis Centers. A fundamental difference exists, however, since the functional responsibility of the Remote Control Station is control instead of analysis, although the analytic function is still required.

BASIC ORGANIZATIONAL CONCEPT

The hierarchical nature of decision making within large systems, such as the Space Flight Operations Facility, indicates that the organization of personnel will be an important aspect of RCS design. Although the number of personnel required for the system cannot be specified at this time, the number of parameters of concern and JPL's experience on SURVEYOR, MARINER, and RANGER indicate that a multiman system will be required. Qualitative evidence from numerous other systems indicates that the

[1] Reconfiguration is used to denote electronic and thermal, as well as physical state changes.

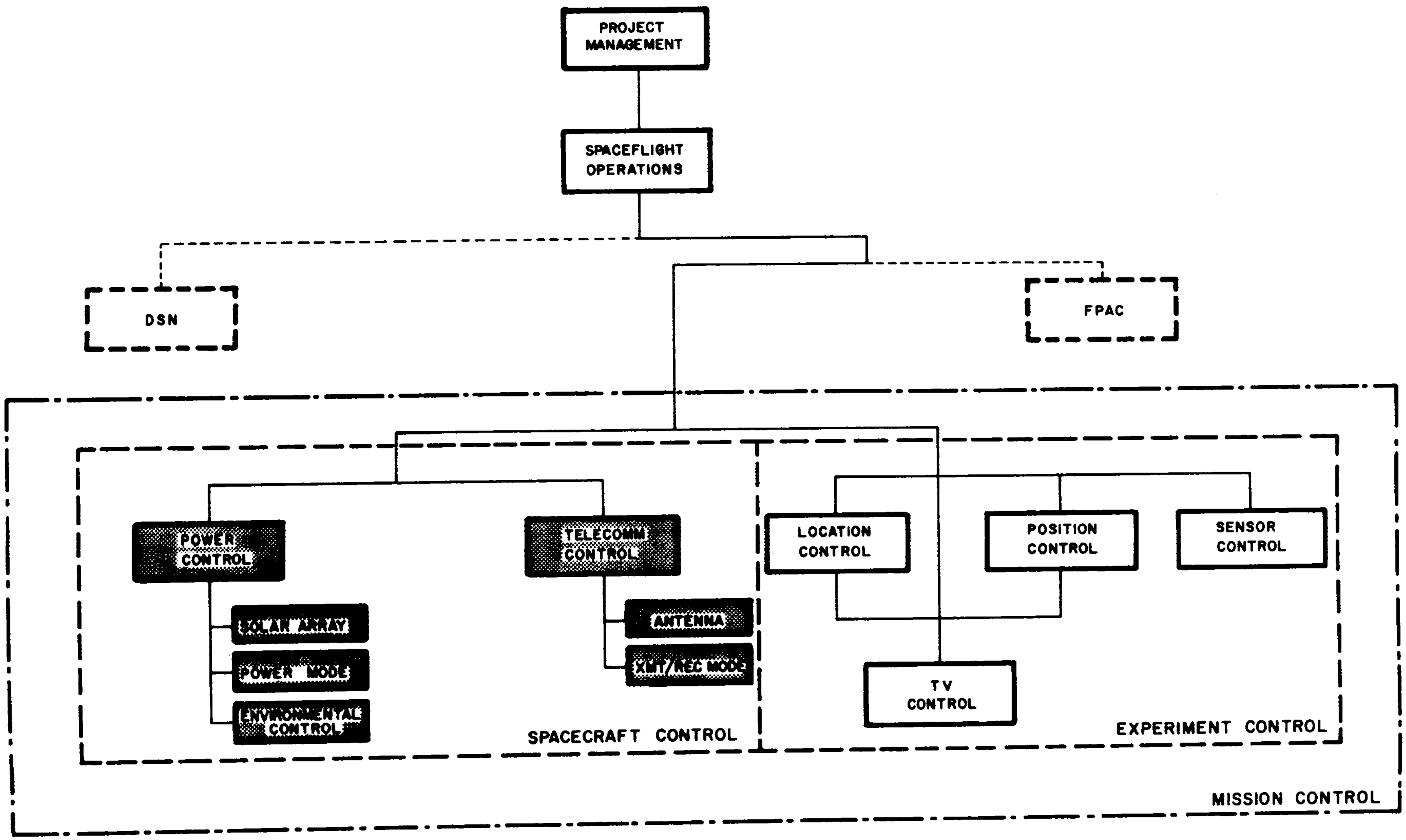

FIGURE 3-5. BASIC RCS ORGANIZATIONAL STRUCTURE

organization of those personnel in terms of decision-making echelons is critical to system performance. Furthermore, an organizational structure serves as a useful framework for organizing the means (both man and machine) since the means must operate as an organizational entity. The organizational structure will dictate, to some extent, the hierarchy of displays and communications between and within echelons. Consequently, the organizational structure of the RCS was examined next in conceptualizing the RCS design. The functional responsibilities of the organizational elements denoted in figure 3-5 are described in the following paragraphs.

SPACE FLIGHT OPERATIONS (SFO)

Headed by the Space Flight Operations Director (SFOD), this organization is comprised of both mission-dependent and independent functional groups. They include the Deep Space Net (DSN) organization assigned to support the operation, the Flight Path Analysis Center (FPAC), and the Mission Control Center (MCC). The latter group is oriented toward the actual control of the spacecraft subsystems, while the other two groups serve primarily in supportive roles. The remote control station (RCS), as defined for this study, is that organizational entity identified as the MCC.

Mission Control Center (MCC)

The responsibilities of the MCC are to monitor all activities, approve commands that are considered critical and not subject to local option, interpret and revise the overall mission plan, and direct and coordinate the various control and analytic function required for the mission. This center is organized into two basic control groups, the Experiment Control Group (ECG) and the Spacecraft Control Group (SCG). These groups are not dissimilar to the Space Sciences Analysis Center (SSAC) and the Spacecraft Performance Analysis Center (SPAC) except that the ECG and the SCG are control-oriented, not analysis-oriented. It is suggested for this concept that the SSAC and SPAC functions be absorbed within these control groups, particularly those functions requisite to control.

Experiment Control Group (ECG)

The EGG assumes the leading role in the control of the spacecraft, except during periods where propulsive or attitude change are to be effected. These changes are based upon the recommendations of the FPAC and may be executed from a console within the Mission Control Center. The ECG effects control of the spacecraft by means of control stations. For the typical spacecraft, the following control stations are recommended. Subsequent analysis may indicate that various stations should be combined; however, the control function exists whether depicted separately or as an integrated station.

Sensor Control Station (SCS)

The Sensor Control Station's functional responsibilities include:

1. Assess received data to determine its meaning, value, and relationship to the experimental plan. This assumes that analysis functions are performed under the direction of or with the cognizance of the SCS.
2. Recommend revisions to the mission plan as a result of this assessment. These recommendations would be relayed to the Mission Control Center for approval and incorporation into the original mission plan.
3. Determine what changes to the spacecraft state are necessary to achieve the experimental objectives.
4. Issue specific commands to effect state changes relevant to the sensor, excluding position and location. Relevant state changes include:
   a. On-off commands
   b. Calibration commands
   c. Gain-change commands
   d. Sensor thermal-control commands
   e. Sensor deployment commands (when mechanized to follow prescribed path).
5. Issue specific direction to collect data from the TV experimental subsystem.
6. Identify the objectives for position and location changes.

Position Control Station (PCS)

The Position Control Station is responsible for responding to the direction of the SCS and effecting the necessary positional state changes. This responsibility usually entails the control of the TV subsystem as well during the course of positional state changes. The PCS responsibilities include:

1. Assess existing and target positions in accordance with SCS requirements.

2. Determine a course of action to achieve target position.

3. Use the TV subsystem, by control or direction, as required to accomplish tasks.

4. Issue specific commands necessary to achieve positional objectives.

Location Control Station (LCS)

The Location Control Station is charged with controlling location changes necessary to data collection. As a result, target information is provided to the LCS by the SCS at varying levels of specificity commensurate with overall data-collection objectives. The LCS function includes the following responsibilities:

1. Assess terrain characteristics pertinent to vehicle control.

2. Issue commands to TV subsystem as necessary to determine vehicle paths to achieve designated targets.

3. Issue commands to locomotion subsystem to pursue selected course of action consistent with experimental objectives and vehicle characteristics.

TV Control Station (TVCS)

The TV subsystem is used both as an experiment and as a supportive subsystem. Its control is by a primary TV Control Station during its use as an experiment. Since use of the TV subsystem is instrumental to location and position state-change control, it is suggested that TV control for these functions be effected from a secondary TV console at these control stations. This requires added TV control means; however, the secondary consoles need provide camera positioning only and can be considered as an extension of the basic TVCS. Functional responsibilities of the TVCS include:

1. Respond to experimental objectives as directed by the SCS.

2. Issue specific commands to obtain desired camera parameters and image quality.

3. Coordinate with TVGDHS.

4. Provide backup to Location/Position Control Station TV-control console.

Spacecraft Control Group (SCG)

The Spacecraft Control Group maintains the operational spacecraft in a state that experimental objectives, as defined by the Experiment Control Group, may be conducted. Since most of the required spacecraft state changes are a direct result of ECG objectives, the control of the spacecraft is keyed closely to the state changes desired by the Sensor Control Group. Thus, they may be treated as a type I control problem, i.e., known response required from a known initiating source. The SCG is subdivided into basically two functional stations — Power Control Station (PCS) and Telecommunications Control Station (TCS). These control stations have the following functional responsibilities:

Power Control Station (PCS)

The Power Control Station is responsible for:

1. Monitoring power state.

2. Monitoring environmental state.

3. Regulating power input (positioning of solar array included).

4. Advising users of existing and projected power states.

5. Inhibiting overloads.

6. Selecting proper mode in response to user requirement.

7. Regulating thermal states of spacecraft (excluding sensor thermal states).

Telecommunications Control Station (TCS)

The telecommunications link, or data transfer system, has basically two functional responsibilities: to mechanically position the antenna array for proper transmission and reception, and to electronically match the spacecraft configuration with the requirements of the user. In the Telecommunications Control Station, the following are considered as primary

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tasks:

1. Control antenna alignment.

2. Respond to user objectives (in a type I control manner) to provide proper receiver, transmitter, antenna, and commutation mode.

3. Advise user of adverse states.

ALTERNATE ORGANIZATIONAL CONCEPT

An alternate organizational structure is illustrated in figure 3-6. The basic difference between this concept and the previous one is that the existing analysis centers would be retained and used in an advisory capacity to the control groups. Spacecraft location changes are considered to be one of the responsibilities of the spacecraft control group; therefore this station has been moved to the SCG.

Another difference between the basic and alternate organizational structures is that the role of the DSN personnel is removed from that of supportive to advisory. This implies that Project Management (considered outside the Remote Control Station) has access to the necessary resources required by Mission Control. The functional blocks, Spacecraft Control and Experiment Control, denote an echelon of responsibility between Mission Control and the individual subsystem control stations.

An advantage of this organizational concept is a well defined separation between the spacecraft control and experiment control responsibilities. Retaining the existing analysis centers on an equal footing with the control centers may lessen personnel resistance to an organizational change.

The basic organizational structure appears to offer advantages when much of the spacecraft control is effected with the assistance of automatic devices, whereas the alternate structure appers to be well-suited when control is performed primarily by personnel.

MEANS DESIGN CONCEPT

The organizational structure discussed above provides a framework for allocating means to meet the functional requirements. However, the means must first be identified. In order to identify possible sets of means, it was necessary to work with the lowest level of requirements information available. The means thus identified could then be organized around the organizational framework and revisions made to the operational concept as a result of: (1) common informational requirements between functional control stations, (2) quantity and frequency of command instructions originating from a station, and (3) the degree of automation to the introduced into the control concept.

To enable the development of a means concept that would incorporate these factors, several figures and tables were employed. These include: (1) a matrix of informational requirements for each identified Remote Control Station responsibility; (2) tabulations summarizing the results of the Remote Control Station means analysis; (3) block schematic diagrams of the functional control stations showing the interrelationship of selected means; and (4) an activity flow diagram of a typical computer/man control process that illustrates the role that the means would play in the RCS.

A matrix of informational requirements versus the RCS functional responsibilities was constructed to assist in determining common requirements between control stations. This matrix is presented in figure 3-7. The informational requirements are not necessarily inclusive nor at a common level of detail; however, they are considered to be sufficiently detailed and inclusive to allow command/control elements to be allocated to the stations. The cell entries indicate what information is deemed necessary for each RCS function. The information may not be presented by an identical display nor in an identical format, but is anticipated to vary with:

a. The purpose of the information,
b. The number of times it is used,
c. The required accuracy of the information.

In developing the matrix the following definitions and ground rules were used:[1]

Assessment is defined as the act of estimating the true state of a system or component from telemetry data, knowledge of the spacecraft characteristics, previous commands issued, and image

[1] A more complete definition of the Remote Control Station functions can be found in chapter II.

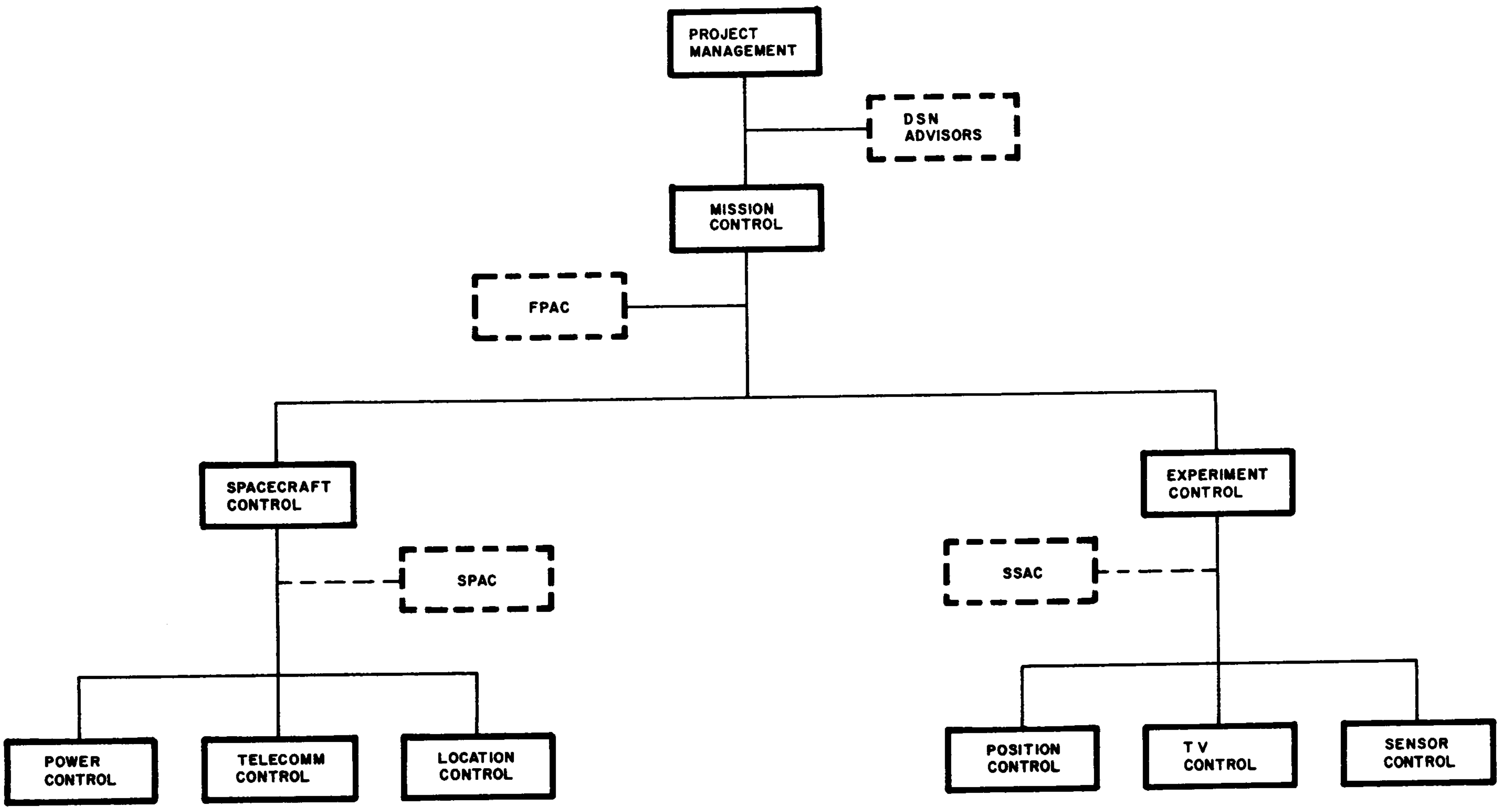

FIGURE 3-6. ALTERNATE RCS ORGANIZATIONAL STRUCTURE

RCS Organizational Element		RCS Functional Responsibility	Locomotion Commands	Location Historical Data	Required S/C Steering Angle	S/C Steering Angle	Required S/C Heading	S/C Heading	Vehicle Status (Rover)	1) Temperature	2) Operational Characteristics	Target Location	Terrain Characteristic	1) Slope	2) Protuberances	3) Depressions	4) Trafficability (Surface Hardness)	TV Commands	TV Image	Camera Azimuth	Required Camera Azimuth	Camera Elevation	Required Camera Elevation	Camera Focal Length
SPACECRAFT CONTROL GROUP	TELECOMMUNICATIONS CONTROL STATION	ASSESS INFORMATION TRANSFER																						
		ASSESS ANTENNA POSITIONING																						
		DCA INFORMATION TRANSFER *																						
		DCA ANTENNA POSITION											●											
		EXECUTE INFO TRANS. CHANGES																						
		EXECUTE ANTENNA POSITION																						
	POWER CONTROL STATION	ASSESS AUXILIARY POWER																						
		ASSESS SOLAR ARRAY POSITION																						
		ASSESS S/C THERMAL STATE																						
		DCA AUXILIARY POWER																						
		DCA SOLAR ARRAY POSITION																						
		DCA S/C THERMAL STATE																						
		EXECUTE AUXILIARY POWER CHANGES																						
		EXECUTE SOLAR ARRAY CHANGES																						
		EXECUTE THERMAL CHANGES																						
EXPERIMENT CONTROL GROUP	SENSOR CONTROL STATION	ASSESS NON-DEPLOYABLE EXPER																						
		ASSESS DEPLOYABLE EXPER																●					
		DCA NON-DEPLOYABLE EXPER																						
		DCA DEPLOYABLE EXPER																	●					
		EXECUTE NON-DEPL EXPER CHANGES										●												
		EXECUTE DEPL EXPER CHANGES										●							●					
	POSITION CONTROL STATION	ASSESS POSITION OF EXPER												●	●	●			●	●		●		●
		DCA OF EXPER POSITION										●		●	●	●			●					
		EXECUTE EXPER POSITION CHANGE										●		●	●	●			●					
	LOCATION CONTROL STATION	ASSESS SPACECRAFT LOCATION	●	●				●	●	●				●	●	●	●			●		●		●
		DCA OF LOCATING SYSTEM			●	●	●	●	●	●	●	●		●	●	●	●							
		EXECUTE RELOCATION			●	●	●	●			●	●		●	●	●	●							
	TV CONTROL STATION	ASSESS TV STATE						●										●	●	●		●		●
		DCA OF TV SYSTEM						●				●						●	●	●	●	●	●	●
		EXECUTE TV CHANGES																			●		●	
MISSION CONTROL GROUP	COORDINATION/ REVIEW STATION	ESTABLISH PRIORITY										●												
		REVISE MISSION PLAN																						
		SEQUENCE INDIVID COMMANDS	●							●	●							●						
		REVIEW CRITICAL EVENTS	●	●														●	●					
		REVIEW FOR REASONABLENESS	●															●	●					

RCS Functional Responsibility	Required Focal Length	Current Camera Focus	Reference Target Focus	Distance to Target	Colorimetric Target (Calibration)	Current Filter Requirement	Aperture Filter Setting	Illumination	Required Depth of View	Shutter Speed	TV Picture Quality	S/C Comm. Subsys. Characteristics	Commo. Commands	Commutation Mode	Xmitter Mode	Xmitter Selection	Antenna Pointing	Antenna Selection	Signal Quality	Absence of Signal	Command Not Received	Command Received In Error
ASSESS INFORMATION TRANSFER													●	●	●	●		●	●	●		
ASSESS ANTENNA POSITIONING														●			●	●	●	●		
DCA INFORMATION TRANSFER *												●	●	●	●	●					●	●
DCA ANTENNA POSITION												●			●		●	●				
EXECUTE INFO TRANS. CHANGES																						
EXECUTE ANTENNA POSITION																						
ASSESS AUXILIARY POWER														●								
ASSESS SOLAR ARRAY POSITION														●								
ASSESS S/C THERMAL STATE														●			●					
DCA AUXILIARY POWER												●										
DCA SOLAR ARRAY POSITION												●					●					
DCA S/C THERMAL STATE												●					●					
EXECUTE AUXILIARY POWER CHANGES																						
EXECUTE SOLAR ARRAY CHANGES																						
EXECUTE THERMAL CHANGES																						
ASSESS NON-DEPLOYABLE EXPER														●								
ASSESS DEPLOYABLE EXPER											●			●								
DCA NON-DEPLOYABLE EXPER												●					●					
DCA DEPLOYABLE EXPER												●					●					
EXECUTE NON-DEPL EXPER CHANGES																						
EXECUTE DEPL EXPER CHANGES																						
ASSESS POSITION OF EXPER		●				●					●			●								
DCA OF EXPER POSITION												●										
EXECUTE EXPER POSITION CHANGE																						
ASSESS SPACECRAFT LOCATION		●				●					●											
DCA OF LOCATING SYSTEM												●					●					
EXECUTE RELOCATION																						
ASSESS TV STATE		●	●			●	●	●		●	●			●								
DCA OF TV SYSTEM	●	●		●	●	●	●	●	●	●	●	●										
EXECUTE TV CHANGES	●			●	●																	
ESTABLISH PRIORITY																						
REVISE MISSION PLAN																						
SEQUENCE INDIVID COMMANDS												●	●									
REVIEW CRITICAL EVENTS													●							●	●	●
REVIEW FOR REASONABLENESS													●									

RCS Functional Responsibility	Console/Displ Op Procedures	S/C Operating Procedures	Other Components in Operation	Allowable Operations	Standard/Non-Std Opn Procedures	Occurrence of Significant Event	Day/Night Cycle (Ephemeris)	S/C Attitude	Ephemeral Data	Power Commands	S/C Thermal Characteristics	DSIF In View	Power Constraints	Solar Angle	No. of Chg/Dischg Cycles	Sensor Temp. and Limits	Loads In Use	Heater States	Heat Block Stats.	Power Availability	Charge/Discharge Rate	Heat Rejection Characteristics (S/C)
ASSESS INFORMATION TRANSFER		●										●				●				●		
ASSESS ANTENNA POSITIONING								●	●													
DCA INFORMATION TRANSFER *			●	●	●						●	●										
DCA ANTENNA POSITION			●	●	●		●	●	●		●			●								
EXECUTE INFO TRANS. CHANGES	●	●																				
EXECUTE ANTENNA POSITION	●	●						●	●													
ASSESS AUXILIARY POWER										●					●		●			●	●	
ASSESS SOLAR ARRAY POSITION								●		●				●							●	
ASSESS S/C THERMAL STATE			●					●		●	●			●		●	●	●	●			
DCA AUXILIARY POWER		●	●	●	●		●			●	●		●		●	●	●	●		●	●	
DCA SOLAR ARRAY POSITION		●	●	●	●		●	●	●	●	●		●	●						●		
DCA S/C THERMAL STATE		●	●	●	●		●	●		●	●		●	●		●	●	●	●	●		●
EXECUTE AUXILIARY POWER CHANGES	●																					
EXECUTE SOLAR ARRAY CHANGES	●							●	●													
EXECUTE THERMAL CHANGES	●																					
ASSESS NON-DEPLOYABLE EXPER			●			●	●	●			●					●	●					
ASSESS DEPLOYABLE EXPER			●			●	●	●			●					●	●					
DCA NON-DEPLOYABLE EXPER		●	●	●	●			●									●			●		
DCA DEPLOYABLE EXPER		●	●	●	●			●									●			●		
EXECUTE NON-DEPL EXPER CHANGES	●						●	●														
EXECUTE DEPL EXPER CHANGES	●						●	●														
ASSESS POSITION OF EXPER								●														
DCA OF EXPER POSITION		●	●	●	●	●		●					●			●	●			●		
EXECUTE EXPER POSITION CHANGE	●																					
ASSESS SPACECRAFT LOCATION								●														
DCA OF LOCATING SYSTEM		●	●	●	●	●		●					●			●	●			●		
EXECUTE RELOCATION	●							●														
ASSESS TV STATE							●	●								●						
DCA OF TV SYSTEM		●	●	●	●			●					●	●		●	●			●		
EXECUTE TV CHANGES	●																					
ESTABLISH PRIORITY			●			●	●	●			●	●	●		●		●			●		
REVISE MISSION PLAN						●					●											
SEQUENCE INDIVID COMMANDS		●			●					●	●											
REVIEW CRITICAL EVENTS						●				●							●					
REVIEW FOR REASONABLENESS	●	●	●	●	●					●	●		●			●	●					

RCS Functional Responsibility	Solar Array Pointing	Position Commands	Extension, Positioning	Azimuth, Positioning	Elevation, Positioning	Experiment Plan	Exper Op Procedures	Experiment Priorities	Responsibility/Authority Assignments	Data from Sensor (Engr. or Sci.)**	DSN Status	Ground Resource Availability	Allocated Experiment Time	Elapsed Experiment Time	Data from Other Operations ***	Commands Previously Issued	Exper Commands	Sensor Calibration Data	Data Collection Requirements	Existing Sensor Location	Existing Sensor Position	Sensor Gain Setting
ASSESS INFORMATION TRANSFER						●		●		●	●		●			●			●			
ASSESS ANTENNA POSITIONING										●						●						
DCA INFORMATION TRANSFER *						●		●			●		●						●			
DCA ANTENNA POSITION	●																					
EXECUTE INFO TRANS. CHANGES									●													
EXECUTE ANTENNA POSITION									●													
ASSESS AUXILIARY POWER										●						●						
ASSESS SOLAR ARRAY POSITION	●									●						●						
ASSESS S/C THERMAL STATE	●									●						●						
DCA AUXILIARY POWER	●					●		●					●						●			
DCA SOLAR ARRAY POSITION	●																					
DCA S/C THERMAL STATE	●																					
EXECUTE AUXILIARY POWER CHANGES									●													
EXECUTE SOLAR ARRAY CHANGES									●													
EXECUTE THERMAL CHANGES									●													
ASSESS NON-DEPLOYABLE EXPER						●		●		●			●		●	●	●	●	●	●		●
ASSESS DEPLOYABLE EXPER			●	●	●	●		●		●			●		●	●	●	●	●	●	●	●
DCA NON-DEPLOYABLE EXPER						●	●	●					●	●				●	●	●		●
DCA DEPLOYABLE EXPER			●	●	●	●	●	●					●	●				●	●	●	●	●
EXECUTE NON-DEPL EXPER CHANGES									●													
EXECUTE DEPL EXPER CHANGES									●													
ASSESS POSITION OF EXPER		●	●	●	●					●						●					●	
DCA OF EXPER POSITION		●	●	●	●	●	●	●					●	●					●		●	
EXECUTE EXPER POSITION CHANGE									●													
ASSESS SPACECRAFT LOCATION										●						●				●		
DCA OF LOCATING SYSTEM						●							●						●	●		
EXECUTE RELOCATION									●													
ASSESS TV STATE										●					●	●		●		●	●	
DCA OF TV SYSTEM						●	●						●					●			●	
EXECUTE TV CHANGES									●													
ESTABLISH PRIORITY						●		●	●	●	●		●	●	●				●	●	●	
REVISE MISSION PLAN						●		●		●		●	●	●	●				●			
SEQUENCE INDIVID COMMANDS		●															●					
REVIEW CRITICAL EVENTS		●													●	●	●					
REVIEW FOR REASONABLENESS		●					●										●					

FIGURE 3-7. RCS INFORMATIONAL REQUIREMENTS VS. FUNCTIONAL RESPONSIBILITIES.

*(DCA), Determine Course of Action

** Form compatible to:
1) Determine quality of data.
2) Determine % completion of objectives.
within ____ time units of event.

*** Including time of occurrence necessary for cross correlation as required.

Fold out Frame I

Fold out Frame II

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information. No attempt is made to determine what the state should be or to predict what steps should be taken in this function.

Determine Course of Action is defined as a function that uses the results of the assessment function, historical data on the performance of the system or component, knowledge of the mechanical characteristics of the equipment under control, experimental objectives which involve the component or system in question, and constraints originating either from time or resources to determine what should be done next; i.e., a course of action. The results of this function may be to do nothing, to conduct predictive exercises on what might happen if a particular course of action is followed, or to recommend that particular steps be executed by transmitting commands to the spacecraft.

Execution is defined as the functional activities necessary to formulate or retrieve the commands corresponding to a particular course of action. Command/control console procedural information, knowledge of supplementary commands required, and a specification of the desired course of action are necessary to accomplish this function.

The basic ground rules used to guide the development of this matrix were as follows:

1. No decision was made regarding the means required to implement the RCS function.

2. The informational content was developed from the RCS command/control requirements contained in tables 2-11 through 2-17, figure 2-15 in chapter II, and figures 3-3 and 3-4 of this chapter. No specification of the informational format or extent of detail was assumed.

3. The organizational elements were derived from the organizational structure shown in figure 3-5.

4. The RCS functional responsibilities were obtained by selecting those functions considered to be the primary concern of the RCS (refer to figures 3-2, 2-14, and 2-16).

Specific informational requirements to conduct analysis necessary for control are a function of the specific equipment being controlled, e.g., a roving vehicle concept may use an odometer to assist in dead-reckoning navigation; therefore, this information will be required. An experiment such as the SURVEYOR Soil Mechanics Surface Sampler requires a real-time display of the strain during lifting operations (converted to a force measurement), whereas a different design may create a need to monitor the current on the driving motor for the same parameter. Specific parameters were not included on the matrix since each spacecraft design requires different specific information. This specificity should be added during later design studies.

The information specified as required for a particular organizational element to perform its designated function was examined to determine:

1. How the information is to be used.
    a. Quantitative computations
    b. Qualitative decision making
    c. Orientation
    d. Procedure
    e. Reference
2. The form in which the information should be presented to the means implementing the function.
    a. Temporary storage
        (1) Computer storage
        (2) Transient displays
            (a) CRT
            (b) Panel meters
            (c) Status indicators
    b. Permanent storage
        (1) Magnetic tape
        (2) Punched paper tape and cards
        (3) Hard copy
            (a) Plots
            (b) Strip charts
            (c) Pictures
            (d) Printouts
3. The anticipated number of changes (and the range) in the information occurring within given units of time.
4. The anticipated frequency with which the information will be used.

The results of this examination were qualitative and are reflected in the tabulations describing the

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individual work station. These tabulations are shown in tables 3-1 through 3-7.

For each of the RCS organizational elements, a matrix of required information by general means was developed with specific means entered in the cells. The entries in these tables provide a basis for constructing an RCS functional block schematic and work-station layouts. Specification of the means at a lower level of detail is a matter of integrating the requirements for control with those for analysis, and applying accepted human factors principles to generate a specific layout.

As previously stated, design is an iterative process of determining functional requirements at successively lower levels of detail, developing concepts for the means to meet those requirements, and modifying previous concepts on the basis of more definitive data. There is no single thread of activities that leads directly to system design, since trade-offs occur at all levels often requiring previously accepted concepts to be altered.

Each control station identified in the organizational structure was treated as an entity in the means analysis. The general means that were selected assumed that the RCS functions for each work station were grouped together and could share common means. The means entries in the table thus were responses to the required information entries, recognizing that the means must serve the "worst case" function.

Many of the entries in the tables were based upon requirements that had been identified through analyses leading up to the means selection. Other entries were based on the best judgment of the analyst in interpreting the needs of the organizational elements selected to control the spacecraft. The information contained in the RCS means-analysis tabulations is expected to require some revision and expansion prior to finalizing the design. The information presented, however, is considered to be at a sufficient level of detail and inclusiveness to permit a design concept to be developed. The specific entries in the tables are, for the most part, self-explanatory; however, some rationale for their selection is presented below.

No breakdown of the Sensor Control functional group (later identified as Sensor Control Work Station) into specific experiments was made since the specific informational requirements are contingent upon the specific experiment aboard the spacecraft. Specific data for analysis should be gathered from the cognizant scientific organization, while the control requirements obtained from these groups should be evaluated for possible overspecification. This assemblage of informational requirements then forms one basis for means selection.

The information categories itemized in column 2 are needed for postmission analysis and were considered to be useful (if not absolutely necessary) for control. It is difficult to establish the extent of analysis required for certain RCS outputs, such as whether the received data are adequate. Since this is one of the Sensor Control functions that will entail analysis during the conduct of a mission, an over abundance rather than a paucity of information may be preferred and, therefore, should be made available (not necessarily in real-time) to the controlling function.

It was also assumed that changes to the mission plan will occur on either a short or long-term basis; that is, the available information may indicate that a revision in the plans or objectives is necessitated immediately or at some longer time after the results have been gained. Historical data would be classed in this category of information. It is difficult to anticipate all contingencies; therefore, furnishing the Remote Control Station with ready access to data normally reserved for postmission analysis may increase the likelihood of overall mission success.

It should be noted that the comments column calls attention to concepts in the formative stage; e.g., the computer program referred to on table 3-1, Sensor Control, indicates that any routine preparatory or terminating spacecraft conditions which can be accomplished by means of ground-issued commands may be addressed by a basic sensor-control command. This basic command would then serve as the address to a command sequence. A single input device is considered adequate for most sensor commands. These formative concepts, once synthesized, provide the basis for the overall Remote Control Station operational concept, and, subsequently, the design concept.

Table 3-1. Remote Control Station Means Analysis

Sensor Control

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
Note: The following RCS functions were considered in developing work stations for command/control. Others were considered as SFOF, GCS, or DSIF functions.	Location State	TV monitor of Location Control Station photo map.	Photomosiac (hardcopy) with entries of: 1. Sensor location 2. Time of location 3. Duration at location	Direction given to Location Control Station via: 1. Intercom 2. Verbal	
Assess (f_2)*	Position State	TV monitor of Position Control Station displays or position.	Printout or plot of: 1. Sensor position 2. Time in position 3. Duration at position	Direction given to Position Control Station via: 1. Intercom 2. Verbal Keyboard input to computer for irreversible positioning commands.	
—— Determine (f_3, f_6) course of action (includes a review at the echelon that the decision is made).	Calibration Data		1. Printout of telemetered calibration data. 2. Reference reading.		
	Telemetry Data 1. Sensor output (computer processed) 2. Temperature of sensor/electronics 3. Gain settings 4. Monitored voltages/ amperage	CRT Panel meters	x, y Plotters Strip Charts Helical Drum Recorders Teletype Printout Computer Printout	I/O console to computer to retrieve commands for: 1. Sensor on/off 2. Heater on/off 3. Gain settings 4. Reset/clear, etc. 5. Calibration	Computer program to generate sensor control may be coupled with computer subroutine to co-ordinate required auxiliary commands to supportive subsystems.
—— Execution (f_7, f_8, f_{14} and release command from f_{13}). (This action originates with the groups accomplishing f_3 and f_4.)	S/C Historical Data 1. Event/Activity (other) 2. Previous Commands 3. Accumulated opn time. 4. Time since last opn.		Printout Strip Chart		
	S/C Status 1. S/C attitude 2. Resource availability 3. Time into mission	Status lights/ status board.	Strip Chart		

* Refers to functions on Figure 2-14

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Table 3-2. Remote Control Station Means Analysis

TV Control

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
Note: The following RCS functions were considered in developing work stations for command/control. Others were considered as SFOF, GCS, or DSIF functions.	Existing Orientation 1. Azimuth 2. Elevation	Dial/Gauge 1. Azimuth 2. Elevation	Strip Chart Az vs. time El vs. time		
Assess (f_2) *	Camera Parameters 1. Focal length 2. Focus 3. Filter 4. Aperture 5. Shutter speed	Alpha-numeric display of camera parameters associated with displayed frame.	Printout of camera parameters vs. time on each frame recorded.	Switches, knobs, buttons, etc. to generate individual commands: 1. Azimuth/Elevation Right Left Rate or step size 2. Focus 3. Focal Length 4. Filter Selection 5. Aperture Setting 6. Shutter Speed 7. Take Mode	Television Command Generation Program (TVCS) desirable for generating command sequences in multiple camera action for steroscopic pictures. S/C mode changes requiring commands, requires interfacing or incorporation into TVCS program.
Determine (f_3, f_6) course of action (includes a review at the echelon that the decision is made).				I/O console to computer 1. Program option switches 2. Templates 3. Keyboard 4. Printer 5. Card reader	
	Desired orientation/ camera parameters.	View of previously received images interpreted to determine required changes in existing TV states.	1. Photomosaic 2. X-Y planar plot with f.o.v. delineated. 3. Predesigned plan for panoramic mapping, colorimetric study, etc.	1. Preprogrammed tape with mission plan. 2. Intercom with SCS and higher echelons.	Television Identification Response Monitor (TVID) compares anticipated ID with actual ID for command sequences generated by TVCS. Proposed stero coverage and point location programs, in conjunction with topographic map generator, to supplement TVCS.
Execution (f_7, f_8, f_{14} and release command from f_{13}). (This action originates with the groups accomplishing f_3 and f_4.)	Temperature of critical elements in TV system. S/C Status 1. Other exper. operation 2. S/C attitude	Gauge/Dial 1. Temp 2. Heater mode indicator Status Board 1. S/C attitude 2. Time into mission 3. Exper. in operation 4. Time into exper.	Strip chart of temp vs. time and event. Printout 1. Commands vs. time and event.	Switch to activate/ deactivate heater.	
* Refers to functions on Figure 2-14.					

Table 3-2. Remote Control Station Means Analysis (continued)

TV Control

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
	Resource Availability	Status Lights 1. Power 2. Telecommunications	Strip Chart Power vs. time and event.	Intercom with SCG.	

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Table 3-3. Remote Control Station Means Analysis

Position Experiment

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
Note: The following RCS functions were considered in developing work stations for command/control. Others were considered as SFOF, GCS, or DSIF functions.	Existing Position 1. Azimuth 2. Elevation 3. Extension	Television Gauge/dial 1. Az 2. El 3. Ext 4. Force/strain	Strip Chart 1. Az vs. time 2. El vs. time 3. Ext vs. time Planimetric map/chart covering sector of interest.	TV controls assumed to be a part of TV control station and adjacent to position control console, voice communication with TVCS.	A 3-D model can be used as a display of existing position when driven by telemetry or as a command generator when positioned manually.
Assess (f_2)* ———	Desired Position/Action 1. Azimuth 2. Elevation 3. Extension	Television to search for target positions and estimated Δ motion required.	Predesigned plan for 1) Az, 2) Ext, with 3) El a variable in absence of topographic data. Planimetric map/chart updated by TV pictures.	Preprogrammed tape with mission plan. Controls for each command. Intercom and voice with SCS.	Note: If model is used, data on its position requires display similar to the remote mechanism. A mode control switch is needed to use same command console for both units.
Determine (f_3, f_6) course of action (includes a review at the echelon that the decision is made).	Experiment parameters associated with positioning mechanism. (See data collection.)	(See experiment control.)			Experiment (sensor controls) that are integrated into positioning mechanism should be controlled by an integrated display/control area.
———	Temperature of critical elements in positioning mechanism.	Dial 1. Temp 2. Heater mode indicator	Strip Chart 1. Temp vs. time and event.	Switch to turn on/off heater.	Environmental control should be part of positioning/experiment mechanism controller's responsibility when it pertains to the sensor or mechanism under control.
Execution (f_7, f_8, f_{14} and release command from f_{13}). (This action originates with the groups accomplishing f_3 and f_4.)	Resource Availability 1. Power 2. Telecommunication 3. Other (TV)	Status Lights 1. Power Go No-Go 2. Telecommunications Go No-Go	Strip Chart 1. Power vs. time and event.	Intercom with SCG.	
	S/C Status 1. Other experiments opn 2. S/C attitude	Status Board 1. S/C attitude 2. Time into mission 3. Experiment in opn 4. Time into experiment	Printout 1. Commands vs. time and event by all controllers.		

* Refers to functions on Figure 2-14.

Table 3-3. Remote Control Station Means Analysis (continued)

Position Experiment

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
	Commands 1. Previously issued 2. To be issued Az, right Az, left El, up El, down El, release Ext, out Ext, in Attachments (Bucket/Scoop/Drill) 1. Open/close/rotate 2. Rates or step size	Status indications on control modes commensurate with each command (e.g., switch position, depressed key, lites, etc.).	Printout of commands vs. time and event.	Switches, knobs, or button keyboard for: 1. Azimuth Right Left Rate or step 2. Elevation Up Down Release/engage Rate or step 3. Extension In Out Rate or step 4. Bucket/Scoop/Drill Open/close/rotate Rate or step size 5. Executes I/O Console to Computer 1. Program option switches 2. Keyboard 3. Overlays 4. Printer 5. Card or tape reader	Command generation program desirable, coupled with TV and S/C mode changes necessary to accommodate positional state changes. Other computer programs with varying degrees of logic may be developed; however, a generic computer program to generate standard sequences or redundant strings including power, environ, telecom, TV, positioning, and sensor control appears feasible and practical. Exceptions require individual command generation capability.

Table 3-4. Remote Control Station Means Analysis

Location Control

RCS Function (1)	Required Information (2)	Displays (3)	Recordings (4)	Controls (5)	Comments (6)
Note: The following RCS functions were oonsidered in developing work stations for command/control. Others were considered as SFOF, GCS, or DSIF functions.	Existing Location 1. Coordinates in relation to landing point or identifiable feature	Television image on CRT.	Photomosaic with cartographic features superimposed.	TV positioning controls duplicated from TVCS.	
Assess (f_2)*	Previous locations and path.	Television images on video tape subject to recall on CRT. Video disc for long term scan coupled to video tape.	Path plotted on map on (b) above with stops indicated by numerals; e.g., 0091-011 could mean the 91st stop for 11 minutes.	Controls to repeat or recall previous TV images.	
Determine (f_3, f_6) course of action (includes a review at the echelon that the decision is made).	Resource Availability 1. Power 2. Telecommunication 3. Other (TV)	Status Lights 1. Power Go No-Go 2. Telecommunications Go No-Go	Strip Chart 1. Power used vs. command.	Intercom with SCG.	
Execution (f_7, f_8, f_{14} and release command from f_{13}). (This action originates with the groups accomplishing f_3 and f_4.)	Desired (target) location and path to reach same. 1. Slope 2. Depression 3. Protuberances	Stero images (TV). CRT view of photomap (4a) with synthetic overlay giving path, hazards, targets.		Intercom with SCS and higher echelons.	Photography interpreted for maneuverability, new targets, etc. Photo interpretation data entered on photomosaic in form of contours, hazards, features, etc. by symbology.
	S/C Attitude 1. Roll 2. Pitch	Panel Meter: 1. Roll 2. Pitch	Strip chart of: 1. Roll 2. Pitch 3. Heading vs. time		

* Refers to functions on Figure 2-14.

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Table 3-6. Remote Control Station Means Analysis
Telecommunication Control

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
Note: The following RCS functions were considered in developing work stations for command/control. Others were considered as SFOF, GCS, or DSIF functions.	Telecommunications System State: 1. Transmitter Selection 2. Antenna Selection (Antenna Mode) 3. Power Level (Xmter Mode) 4. Commutation Mode 5. Receiver Selection	Status Lights	Printout of status vs. time and event.	Computer program to generate commands based upon switch positions and the requirement of communications link users. The latter data is inputed from activating particular consoles within specific work station.	Emergency operation is permitted by manual operation of switch positions that are coupled to a computer driven command generator.
Assess (f_2)*	Temperature	Status lights of temperature extremes driven by a computer sampling incoming telemetry.	Printout of: 1. Temp vs. time. 2. All thermal control commands.	Controlled via the Power Control Station.	
Determine (f_3, f_6) course of action (includes a review at the echelon that the decision is made).	Antenna Position: 1. Elevation angles 2. Azimuth angles 3. S/C attitude 4. Ephemeral data		Plot 1. El angle vs. time. 2. Az angle vs. time. 3. Planetary motions vs. time. Printout All positioning commands.	Keyboard, button, etc. for coupling to computer to generate individual commands. Computer program to generate position commands based upon S/C attitude telemetry data and ephemeral data as well as signal quality data.	Commands required: 1. Periodic during routine mission at Moon (stationary S/C). 2. After S/C motion is completed (Rover). 3. Emergency thermal control. 4. Obscuration preparation. 5. S/C closed loop control for planetary vehicle assumed.
Execution (f_7, f_8, f_{14} and release command from f_{13}). (This action originates with the groups accomplishing f_3 and f_4.)	S/C Status 1. S/C attitude 2. Other subsystem operation	Status Board 1. S/C attitude 2. Time into mission 3. Exper in operation 4. Time into experiment	Printout: All commands to S/C vs. time and event.		

* Refers to functions on Figure 2-14.

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Table 3-7. Remote Control Station Means Analysis

Mission Control

RCS Function 1	Required Information 2	Displays 3	Recordings 4	Controls 5	Comments 6
Review (f_4) (includes all review at higher echelons).	Desired course of action in terms of proposed commands or statement of intent for irreversible and critical commands.	CRT monitor of work stations.	1. Printout of command sequences desired. 2. Log of previous commands correlated to event.	Verbal approval/disapproval via: 1. CCTV 2. Telephone	Mission Control required to physically approve irreversible and critical commands prior to GCS transfer and DSIF transmission. Keyboard at console for this function.
	S/C Status 1. Thermal state 2. Power state 3. Location state 4. Position state 5. Exper in operation 6. Time in exper. 7. Time in mission 8. Exper results 9. Significant events	1. Status Board 2. CRT monitor of work stations.	1. Tabular/diagrammatic info prepared by SCG and ECG. 2. Hardcopy photography.	1. CCTV 2. Telephone	
—	S/C Characteristics 1. Thermal 2. Experiment 3. Power 4. Communications 5. Valid commands		1. Tabulation 2. Plots	Telephone	Supplemented by detailed analysis and comments by specialty groups.
Coordination (f_{13}) (consists of coordinating control activities with support activities, coordination within RCS is accomplished by f_4 or by lateral communication of similar RCS elements).	Commands originating from individual work stations to be integrated into sequence.	Status Lights: 1. Exper, subsystem, and work station involved. 2. Valid/invalid command requests.	Printout of all command requests and transmissions.	I/O console to computer programmed to sequence commands given initiating command (same as I/O console at each work station).	Normally not used except in the event Mission Control must take over the execution of mission.
	Mission Plan 1. Time allocations 2. Power allocations 3. Sequences 4. Constraints 5. Capabilities	Micro film with monitor.	1. Chart 2. Tabulation	Mission plan capable of being addressed by time, experiment, subsystem, objectives, and constraints.	
	DSN Status	Status Board 1. GCS state 2. DSIF state 3. SFOF resources state	Printout of DSN state vs. S/C time and event.	CCTV and telephone with DSN cognizant individuals.	

The means selected to display and record the information was subject to judgment; however, an incorrect selection is not considered critical to the RCS concept. In most cases, an alternate selection does not alter the user requirement for access to the information. Reliance upon computer services will affect the displays needed for control, but should not significantly affect those needed for analysis.

The data-collection supportive subsystems are generally more complex in the degrees of freedom over which control must be maintained. Despite the added complexity, they lend themselves to a more detailed definition. One reason for this is that most spacecraft are similarly configured in this respect, and, consequently, the required supportive subsystems can be identified more readily. Another reason is that analysis is usually required during the controlling process to insure mission completion; therefore, the information itemized in column 2 is assumed to be a control requirement, rather than a postmission analytic one.

Prior to completion of the work-station means analysis, it was recognized that the means selected to meet certain work-station requirements could be shared by one or more other work stations. Means-sharing decisions were based upon the following criteria. The means could be shared if:

1. Simultaneous demands can be serviced, or the service queue is not detrimental to the mission in terms of:
   a. Increased time
   b. Decreased reliability
2. The shared means satisfy or exceed the requirements of each user in regard to:
   a. Informational content
   b. Accuracy
   c. Duration
   d. Legibility
   e. Response
   f. Operational ease
3. The shared means do not cost more than individual means; e.g., one sophisticated or large means may cost more than several simple or small ones.
4. The physical placement of other non-shared means permits access to the shared ones.

Sharing was most evident for display of general information and status data. Recordings of the commands, events, and time can be shared, since this record is needed primarily for analysis. Historical information on the spacecraft performance needed for Mission Control and the analysis groups, can be shared or referred to when needed.

Two or more low-command output stations may be combined so that a common command-initiation device may be used; e.g., the Power Control Work Station and the Telecommunications Control Work Station. When control is not to be conducted concurrently (or nearly so), the command-initiation signals may originate from a single console. Proper use of templates or overlays permit efficient control to be effected using this approach.

The Locomotion Control function and the Position Control function, as well as the Television Experiment, require image information. A single master display of images in a form that will meet the severest requirement of all users appears feasible. For example, location control may require stereo images. Since positioning of experiments by way of mechanical arms or booms is not likely during motion, this display could be used for both control functions.

Further analysis of the selected means and the potentials of commonality was facilitated by constructing block schematic diagrams of each candidate work station. The block schematics are shown in figures 3-8 through 3-13. On these diagrams, the means shown in broken boxes are considered to be external to the Remote Control Station. It should be noted that the means displayed enable the control of each spacecraft function to be effected essentially on an independent basis. Exceptions to this are taken into account by incorporating a software control model and assuming lateral communication via CCTV and telephone.

The similarity in format between work-station block schematics was a deliberate attempt to exhibit the potentials of sharing means as well as standardizing layout. The results of combining the work-station block schematics into an overall Remote Control Station block schematic which incorporates

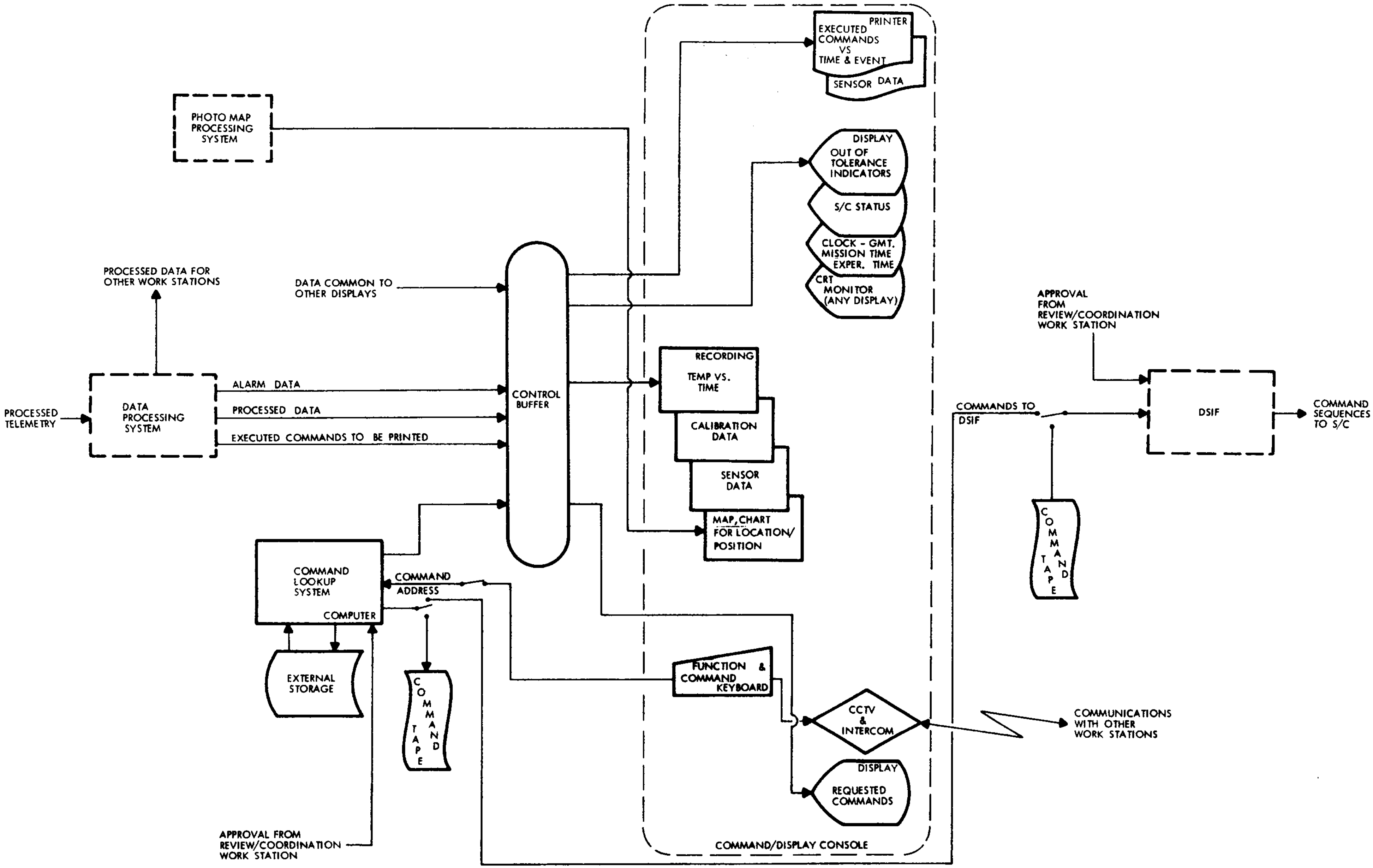

FIGURE 3-8. BLOCK SCHEMATIC OF SENSOR CONTROL WORK STATION.

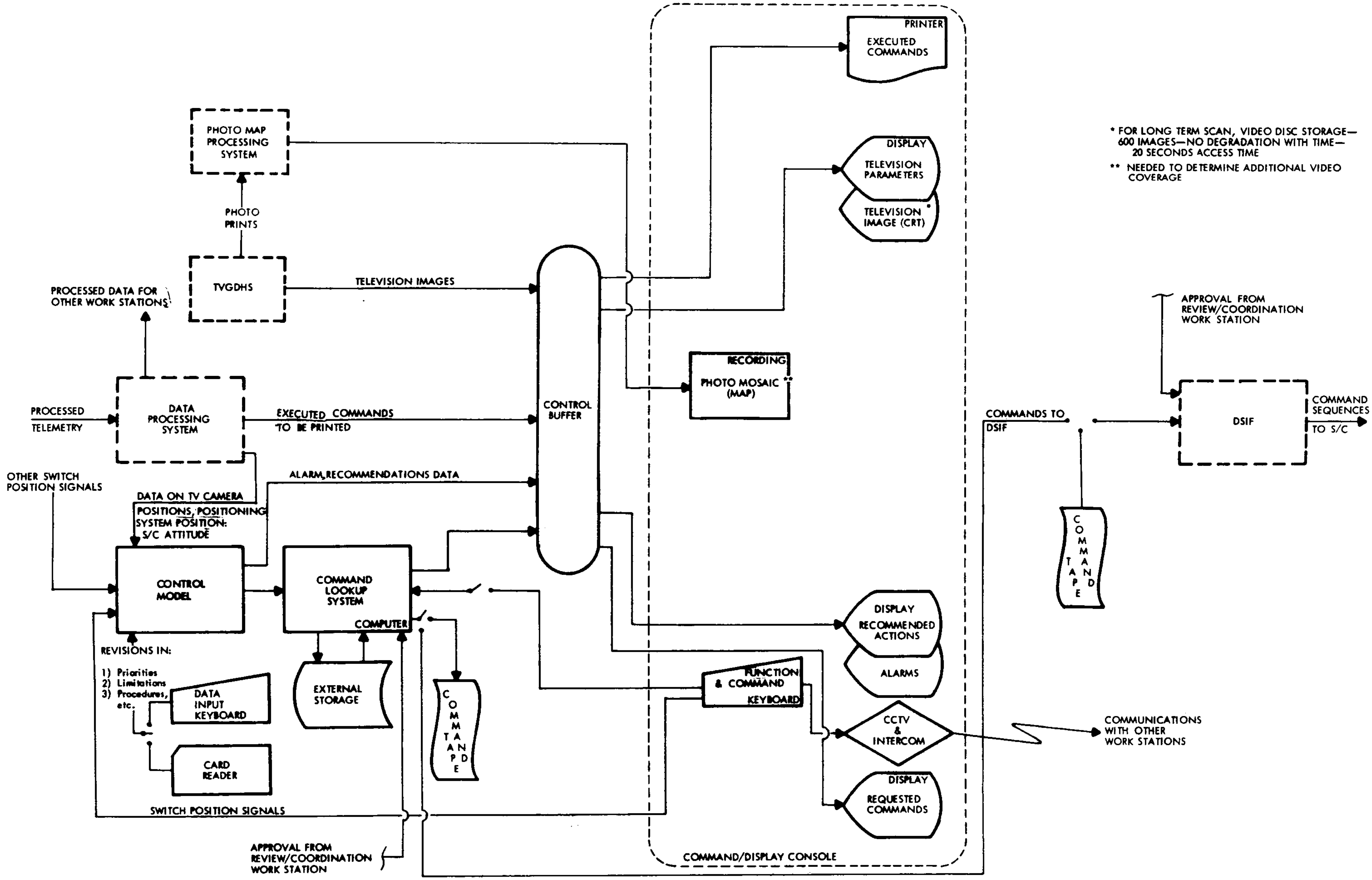

FIGURE 3-9. BLOCK SCHEMATIC OF TELEVISION CONTROL WORK STATION.

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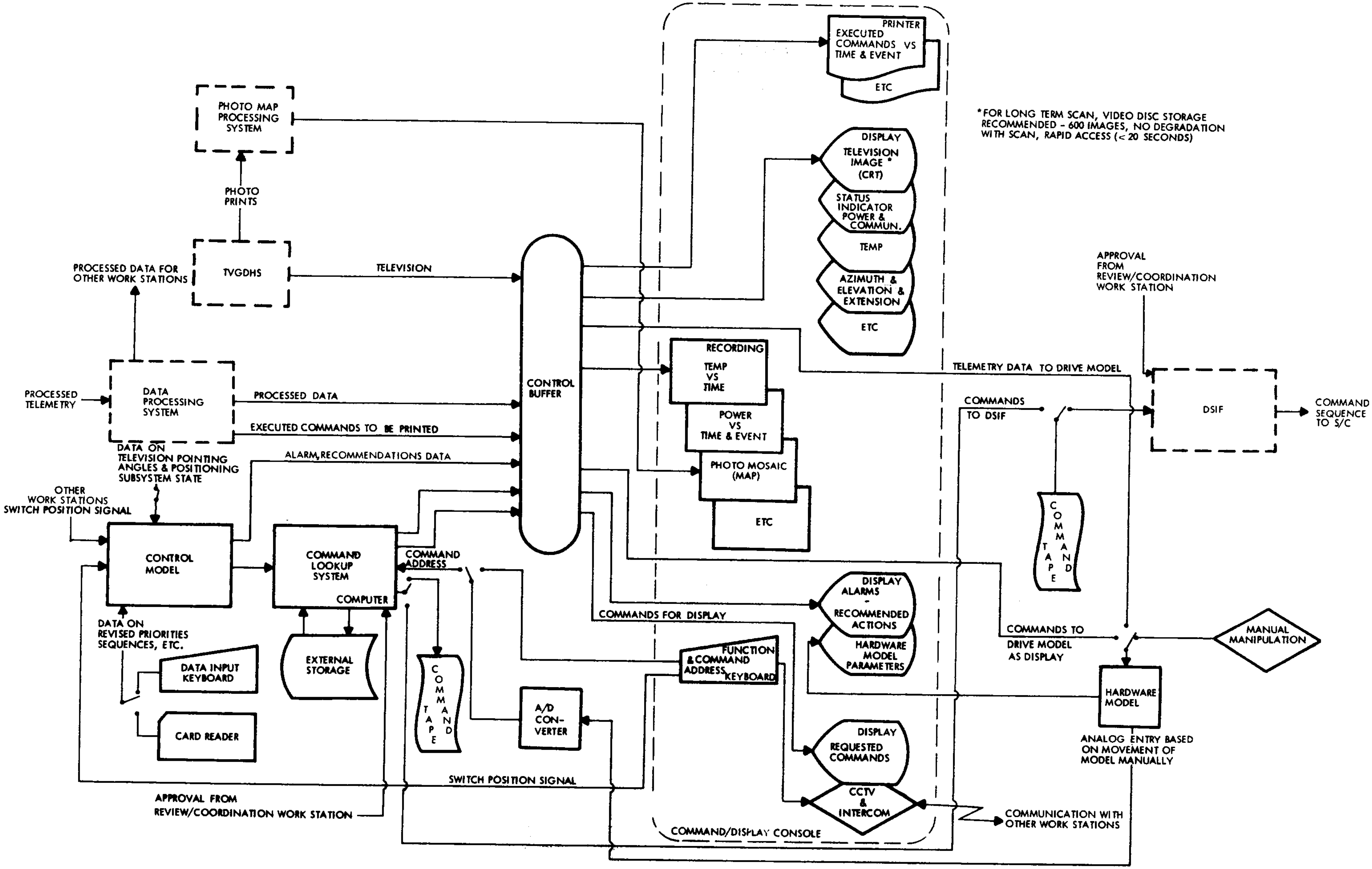

FIGURE 3-10. BLOCK SCHEMATIC OF POSITIONING CONTROL WORK STATION.

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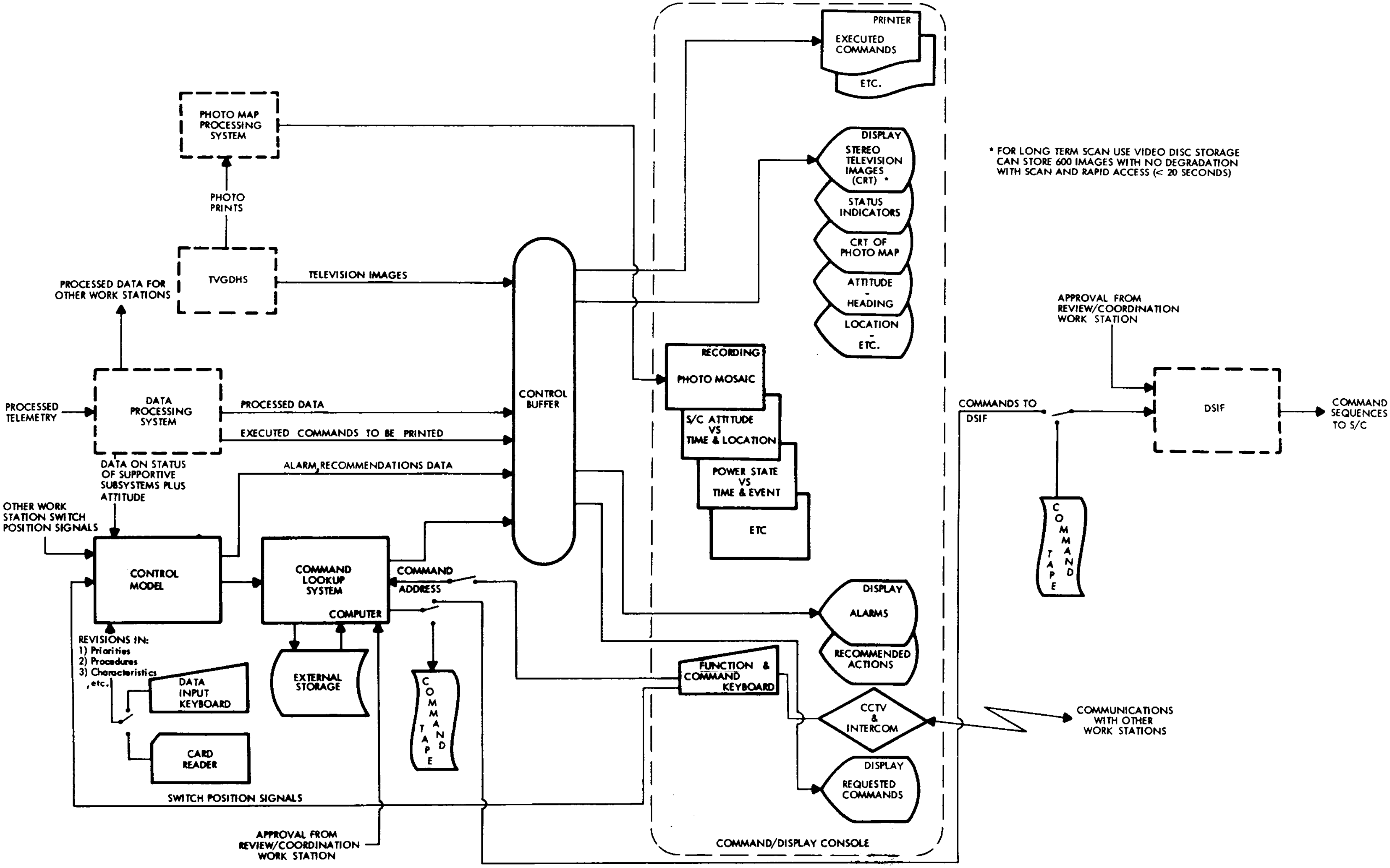

FIGURE 3-11. BLOCK SCHEMATIC OF LOCOMOTION CONTROL WORK STATION.

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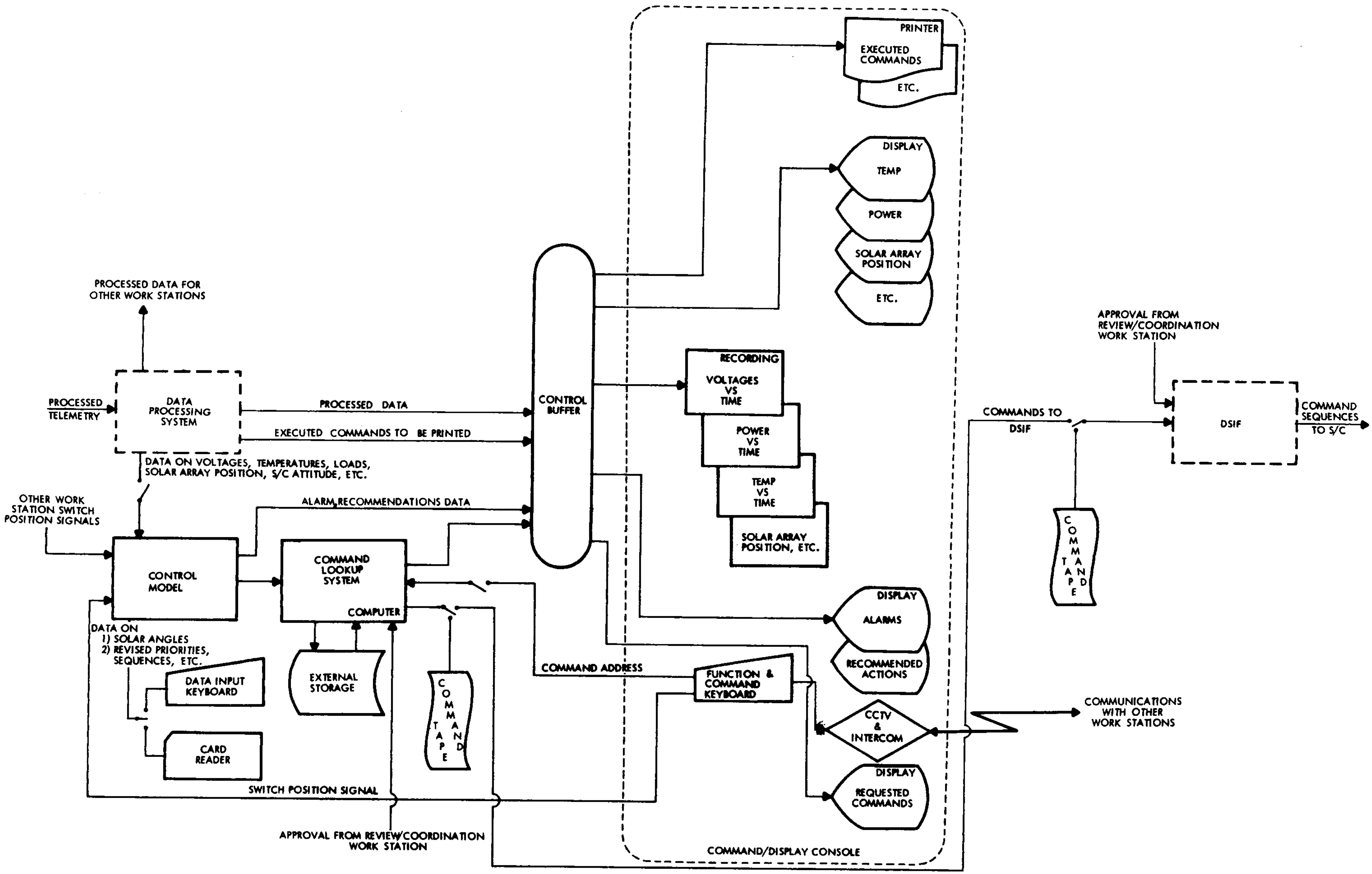

FIGURE 3-12. BLOCK SCHEMATIC OF POWER CONTROL WORK STATION.

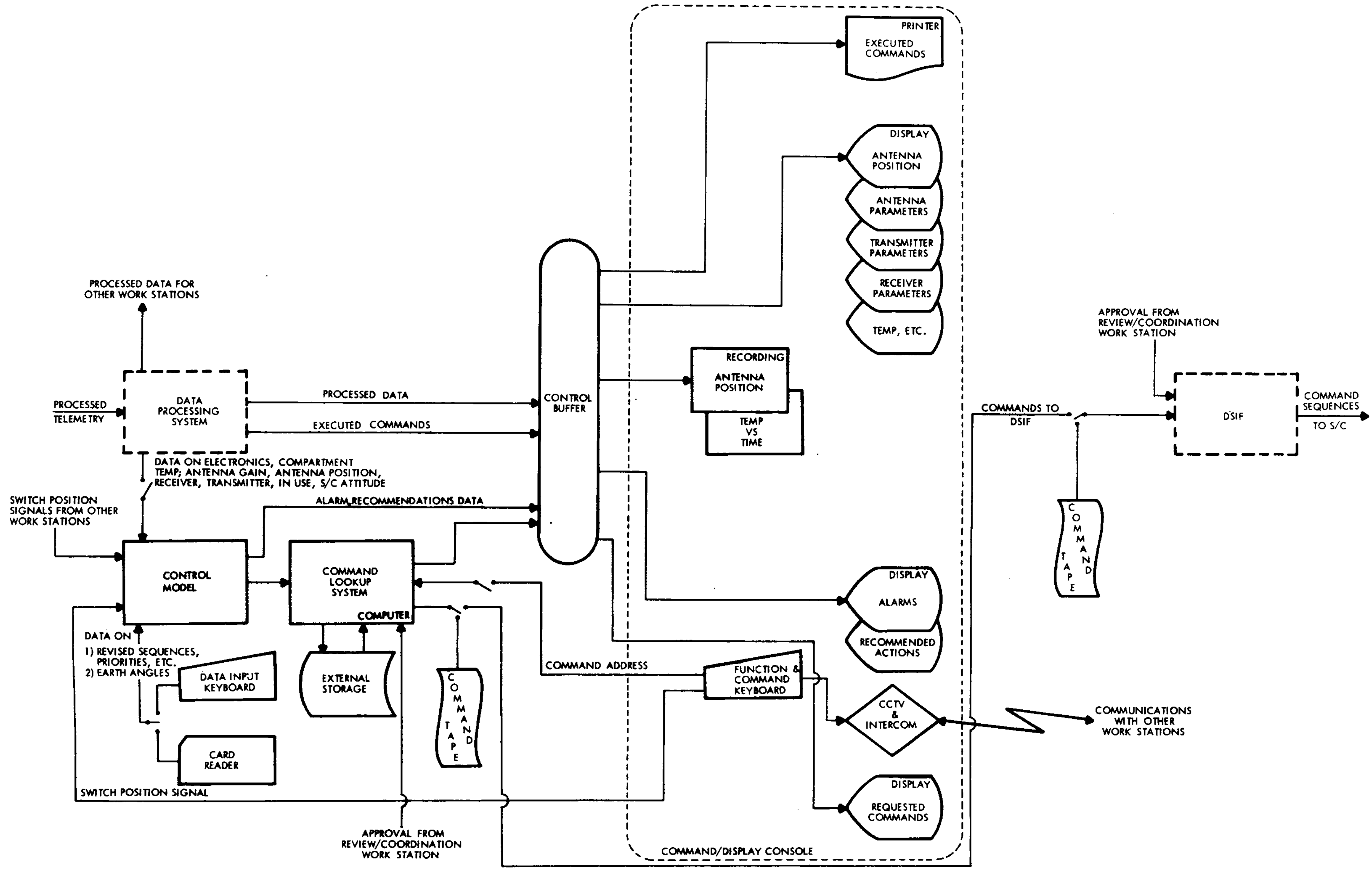

FIGURE 3-13. BLOCK SCHEMATIC OF TELECOMMUNICATIONS CONTROL WORK STATION.

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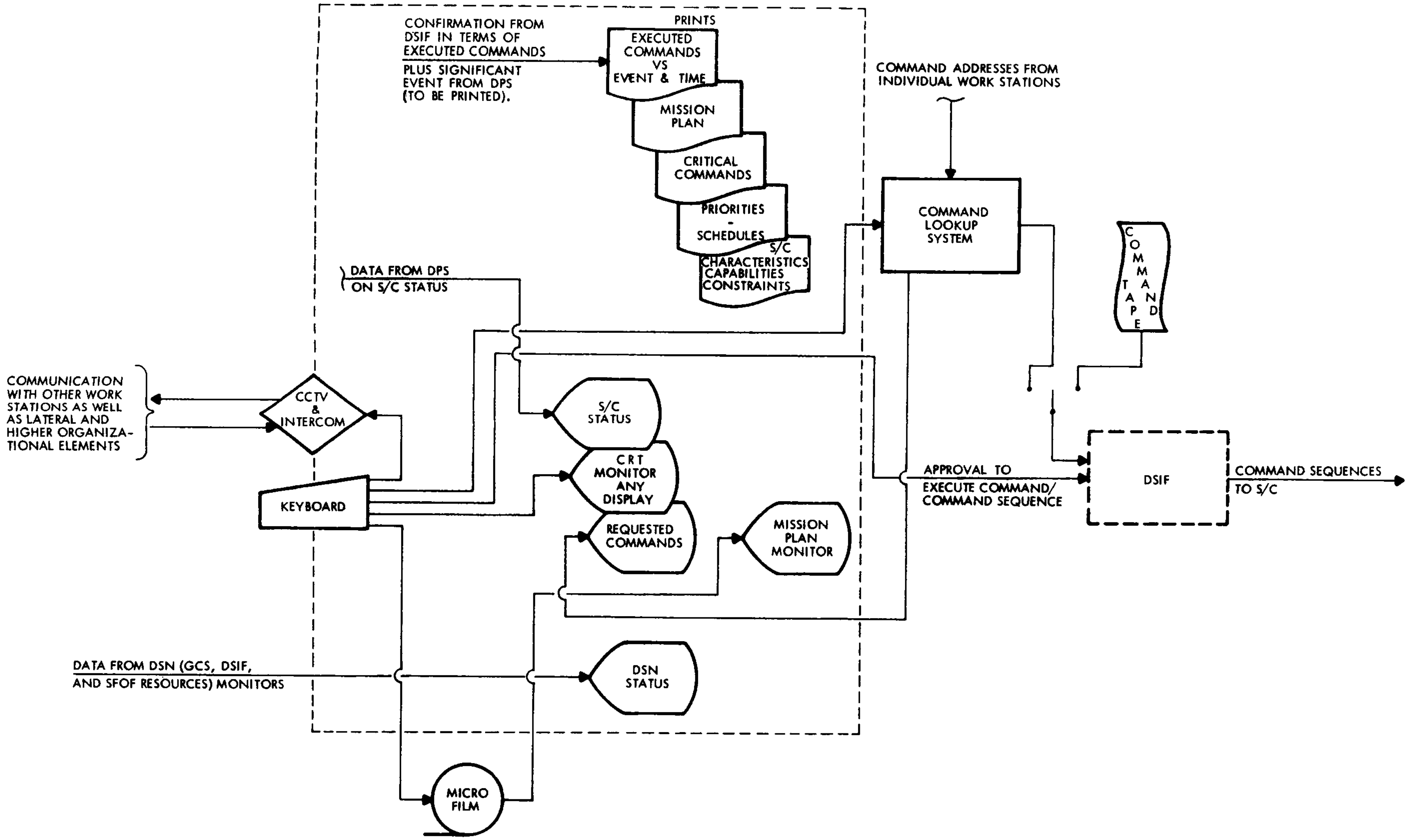

FIGURE 13a. BLOCK SCHEMATIC OF MISSION CONTROL WORK STATION.

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the conclusions of the means-sharing analysis are presented in figure 3-14 (see cover envelope). This block schematic illustrates that control of the spacecraft can be accomplished from integrated command/display means.

The Position and Location Control functions can use a common video-display system since these subsystems will not be in operation simultaneously. A common command-initiation console is feasible if it is provided with mode-selection capabilities. The command-initiation console should also include the positioning controls for television, since this subsystem is instrumental to the success of both reposition and relocation. These controls are required for positioning and execution only, since other commands pertinent to television would be found at the Television Control Work Station.

During operation, the Television positioning commands may be generated, upon initiation from the console, by a computer program which couples the arm or boom pointing angles with those of the television cameras. The computer can also generate commands to drive the camera in orientation during operation with the locomotion subsystem by transforming the spacecraft-fixed axes to lunar-fixed axes. Manually initiated commands can refine the camera pointing angles after the gross movement commands are generated by the computer.

Since the command-generation load is expected to be quite low for the Power Control and the Telecommunications Control Work Stations, and since the motion of steerable antennas and solar arrays is so similar, a single command-initiation console with mode-selection switches was chosen.

The command/display means for Television control should be physically located near the Location/Position control means so that any stereoscopic or photomosaic displays used for motion or position control may be viewed by the TV control personnel.

Sensor control can probably be executed from a single command-initiation console if templates or overlays and mode switches are provided. These means should be located close to the display and command means for experiment positioning, considered as a part of the Locomotion/Position Control Work Station.

It is recommended that the Mission Control Work Station (used for coordination, review, and approval of all aspects of the mission) be located in the immediate vicinity of the operational work stations. This would reduce the number of displays that must be repeated and facilitate communications.

These concepts were synthesized into an artist's rendition of the Remote Control Station showing the relationship of selected means. This illustration (figure 3-15) indicates five functional stations, each provided with the capability to communicate with the computer (control model) and each other. The Mission Control Station represents a reviewing, coordinating, and approving facility, while the remaining four stations provide the operational decision making and execution necessary to spacecraft control.

The layout in this rendition is not drawn to scale and should be considered only in the sense of projecting a picture of the conceptual design of the Remote Control Station. A specific layout of the station might indicate that a more detailed analysis had been conducted than in fact was the case in this phase of the study and is therefore not presented. A functional representation of the Remote Control Station, together with criteria for determining the adequacy of the selected concepts, permits the design conceptualization process to be carried out to its logical conclusion. This is the iterative principle of design.

COMPUTER ROLE IN REAL-TIME CONTROL

The concepts and the means developed in the preceding section include the use of automated devices. The primary automatic means that was assumed is the digital computer. With more complex spacecraft configurations, increased experimental capabilities, and the necessity of real-time control, the operational control of future spacecraft will become significantly more complex. By applying computer capabilities to the operational control function, however, it is believed that the routine control functions can be accomplished automatically, leaving only the qualitative decision processes and the more advanced control functions to be done manually. Some of the factors which must be considered in arriving at the RCS control means are as follows:

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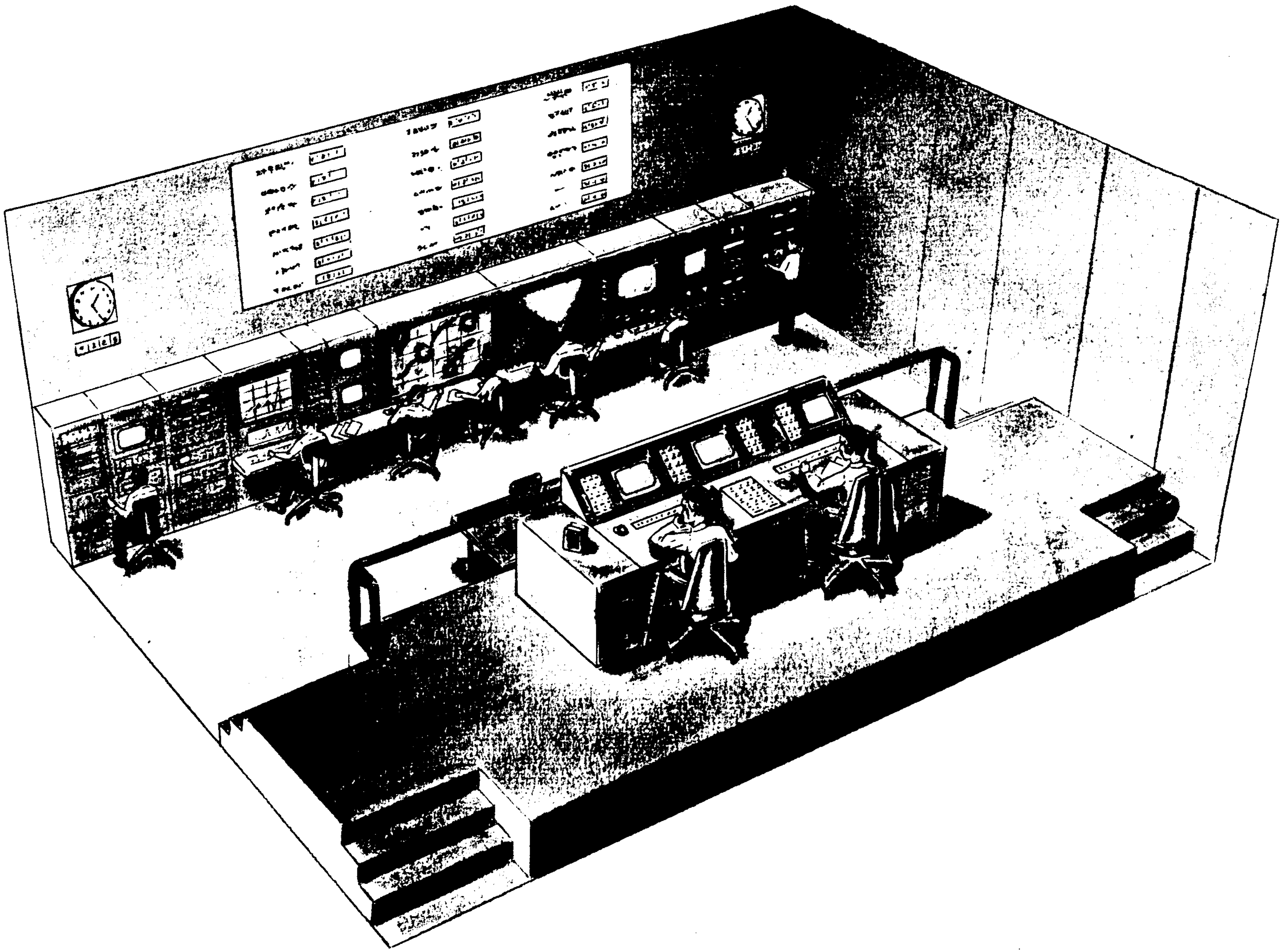

FIGURE 3-15 ARTIST'S RENDITION OF REMOTE CONTROL STATION

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1. The desire to accommodate a variety of spacecraft systems having both lunar and planetary missions which may occur in rapid succession.

2. The desire to minimize modifications of the RCS to control simultaneous but different spacecraft systems.

3. The design details of future spacecraft of concern, which are required to identify specific control-console-design details are not known at this time. Thus, differences between future spacecraft cannot be identified. These include the following:

   a. Experimental techniques;

   b. Performance characteristics of subsystems such as degrees of freedom, response time and accuracy, failure modes and effects;

   c. Resource availability and constraints on simultaneous operations; and

   d. Telecommunication capacity.

To achieve the RCS design objective, it appears that the physical means used for presentation and control should be flexible enough to allow rapid modification at a reasonable cost. Based on a review of the means alternatives discussed above, a concept was selected which appears to satisfy both the detailed functional requirements and the basic RCS design objectives. The approach is based on the concept of programmable consoles wherein the means used for display/interrogation/control are produced by software packages which may be tailored for each specific spacecraft/mission. This approach is predicated on the assumption that generalized RCS control consoles are not possible using the classical hardware approach, and that reconfiguration of hardware would prove too costly and time consuming.

The principal factor in the software approach is the existing and expanding state of computer-driven display/interrogation technology. To date, this technology has developed systems which have the following characteristics.

1. CRT displays capable of presenting alphanumeric characters and curvilinear relationships with excellent resolution.

2. The character control capability allows presentation of synoptic displays of data from a wide variety of sources.

3. Elements of a synoptic display may be changed without affecting other elements of the synoptic display.

4. Inputs to the source computer may be made through the CRT by using a light pen. The nature of the inputs can vary according to the display control program. Examples of this type of input are:

   a. Display modification;

   b. Data processing (in this case the controller identifies the data to be processed and the processing function);

   c. Historical data recall

5. Time-sharing computers capable of handling numerous CRT displays simultaneously.

6. Existing systems program packages for display generation.

A review of these capabilities, specifically those of the IBM ALPINE system, indicates that most, if not all, of the presentation/computation/interrogation requirements identified by the RCS control requirements analysis could be met by such a system. Although the trade-off and effectiveness analyses which would be required to evaluate this concept are beyond the scope of this effort, it is felt that a very significant potential exists in this approach. Some of these potentials are as follows:

1. Rapid decision making made possible by rapid data access and processing capabilities.

2. Direct processing of digital telemetry by a digital system (i.e., digital-to-analog conversions are reduced).

3. Centralized information processing which provides users with rapid access to any data, depending on requirements and organizational structure.

4. An adaptive display which allows the user to modify the presentation as the situation demands.

5. A flexible system which, given the software, may be adapted to a new mission almost immediately.

Although the above concept appears to satisfy the functional requirements of the RCS, it is our opinion that considering the existing JPL facilities and the state of technology of the direct-access computer, a less sophisticated software approach should be adopted.

One level of computer support that appears quite feasible for spacecraft control at this time is described in general terms in the following paragraphs. The cited example is in terms of a control model, or a computer program, designed for use in the control loop.

The primary function of this model is to automate spacecraft control operations as much as possible without reducing man's actual control of the situation. Therefore, all but the lowest-level decision processes (type I decisions) will still be manual functions. However, working in the framework of an automated system, the manual decision process will be facilitated by faster and more adequate data upon which the decision will be based. Even with the lowest-level decision, manual control is maintained by accepting or rejecting automatically-supplied recommendations by a required "Go" or "No Go" signal.

Therefore, the model proposed in this section is not one in which the control of the spacecraft is automated, but rather the routine processes in the operational control are automated to facilitate manual control.

The primary functions accomplished by the automated portion of spacecraft control are as follows:

1. The software program will test the compatibility of the desired subject activity with the ongoing activities and spacecraft status. A "No Go" recommendation will be displayed if, for example:

   a. Subject activity and ongoing activity require common components;

   b. Sufficient power is not available;

   c. One activity will adversely affect the other.

If a "No Go" status is indicated, the software program will investigate the priorities, users, time to completion, etc. of the activities, and based upon these data, it will display pertinent information and recommend further action.

2. For a given activity, the software program will test the status of required components (sensors, transmitter, antenna, receiver, etc.), recommend changes of state of these components to accomplish the activity, and will initiate these changes of state when a "Go" signal is received.

3. The software program will arrange all required commands into the proper form and time sequence, validate them as to accuracy and completeness, and display and initiate them when a "Go" signal is received, or display errors and data voids.

4. The software program can monitor all incoming signals and upon the occurrence of a certain event, display an alarm and/or recommend action.

5. In addition to the above functions, the software program has computational capabilities which will be useful in transforming input date (e.g., converting pointing commands relative to the surface to a form relative to the spacecraft) and for coordinating activities (e.g., coordinating camera movement with boom movements).

Figure 3-16 presents a flow diagram which describes the proposed model. This flow diagram is a general one designed to accommodate any type of spacecraft activity within its framework.

To perform an activity using the techniques described in the model, the required manual functions are:

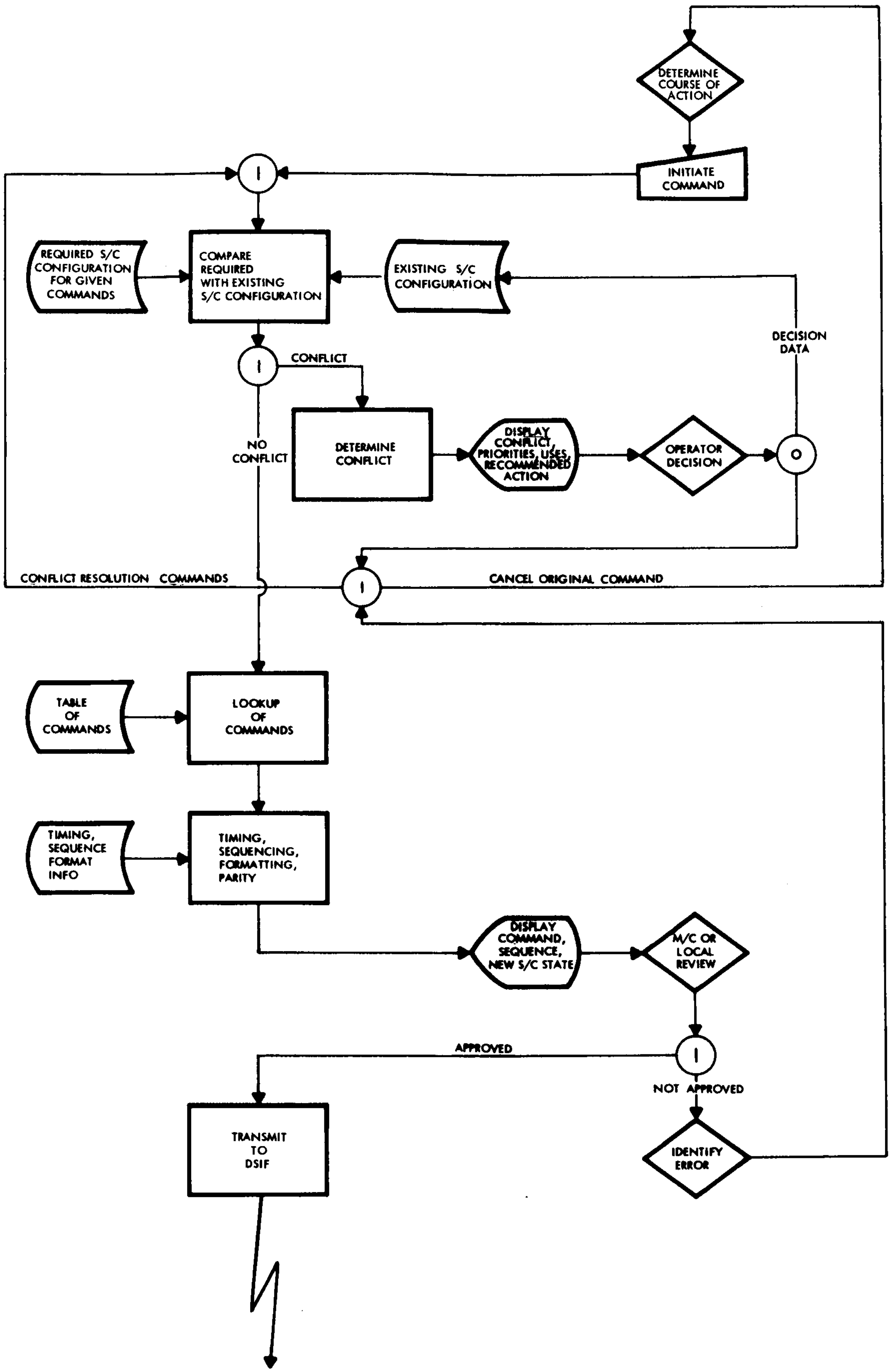

FIGURE 3-16. TYPICAL ACTIVITY FLOW PROCESS FOR REAL-TIME SPACECRAFT CONTROL.

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1. Identify the activity desired.

2. Input primary commands and required designated control commands.

3. Make qualitative decisions when necessary.

The machine outputs of the model would be:

1. Identification of conflicting spacecraft activities or status.

2. Identification of functions requiring qualitative decisions.

3. If the activity checks out to a "Go" status, a display of all required commands in the proper format and time sequence.

A specific example of the control model is given to further clarify the concept. Locomotion control was selected for this purpose. The logical steps that might be followed are described below.

The initiating commands are selected from the Position/Location Control Console such as:

a. Steering angle
b. Step size or speed
c. Number of steps or distance.

These initial commands serve to identify to the computer the activity required, and supplies the basic data required for the performance of the locomotion activity.

The software program then refers to a look-up table which designates the required spacecraft configuration for the locomotion activity. Next the software program compares the required configuration to the one currently being used by ongoing activities. Also, the software program compares the power required for the locomotion activity with the amount of power available. In addition, the software program refers to another look-up table which supplies data as to the compatibility of the activities if one or more activities are in process.

If the software program identifies the subject activity as being precluded for any of the previous reasons, it then displays data as to the priority of each activity, the user, the estimated time to completion, etc., and recommends further action based upon the displayed data and the computer-furnished recommendations. A manual decision must then be made and initiated. One of three alternatives could be chosen:

1. The subject activity could be discontinued.

2. The software program could be instructed to monitor the spacecraft activities, and when the conflicting activity is completed, to continue with the locomotion activity.

3. The software program could be instructed to discontinue the ongoing conflicting activity and to continue with the locomotion activity.

After the system flow passes this point, the software program refers to a look-up table which indicates the required state of specific components. The software program then refers to the present status of each of these components (which is maintained in an additional look-up table), and for those that are not in the proper state, the software program identifies the proper command to bring them into the proper state.

When the system flow has passed this point, the software program refers to a look-up table which contains the required formats and sequencing infomation. The software program then compiles all required commands into the required format and sequence. A validity check for completeness, form, and sequence is then made on these required commands. If there are any errors (suppose the direction of motion, forward or reverse, was not included in the initial data input), the operator will note and correct the omission. If the error is in format, this will be displayed and corrected by the computer.

If there are no errors, or if the errors have been corrected, the software program will display to manual control all necessary commands for approval. If they appear satisfactory, the activation of a "Go" signal will transfer the commands to DSIF for transmission to the spacecraft.

This description of a control model is intended to represent a concept of a computer operating in concert with man, where the control model assists man in executing real-time control. In this way, the judgmental and decision-making capabilities of man can be effectively utilized in an automated control system.

As indicated in the previous chapter, approaches and concepts may be developed to cope with qualitative requirements; however, rarely has satisfactory performance been obtained from a system structured on qualitative requirements alone. Although a system can be designed with little quantitative data at hand, the results can hardly be expected to be as promising as those where all factors significant to design have been delineated and a range of values established.

The conceptual design presented in the preceding section was developed primarily from qualitative requirements. This is not to say that the concept is invalid nor that conceptual designs based on qualitative requirements alone are inherently weak. The implementation of such a concept, however, is more demanding. The assumptions underlying the concept require testing, particularly those assumptions that may result in divergencies in design concepts. By providing quantitative values to those sensitive areas of assumption, a stronger justification for (or rejection thereof) can be made for the resultant solution to specific design problems. Some of the aspects of the Remote Control Station that require quantitative evaluation are discussed below.

QUANTIFICATION OF RELATIONSHIP OF CONTROLLABLE TO UNCONTROLLABLE FUNCTIONS

An underlying assumption to the conceptual design developed in this study was that the functions comprising the Remote Control Station would contribute greater time delays and potentials for error than those functions external to the RCS. Further, it was assumed that implementation of RCS design can be controlled since it is the object of the design study, but the means for the interfacing functions are relatively fixed to those currently in use (for the time period involved). An exception to this assumption was made in the means to transfer command sequences between the RCS and the DSIF. In this instance, a form of a direct-couple system was assumed. To test the basic concept derived in the preceding section, the relationship between the elapsed times and the functional reliabilities within the RCS functions and the functions that are necessary for control within the adjacent system should be determined. This relationship is important since long time delays in adjacent functions may override any advantages of shortening the time delays in the RCS.

Statistical data on time delays and error probabilities within the existing JPL command system (particularly within the adjacent systems) can provide one set of values. Data on expected time delays and error rates for the pertinent RCS functions can be gained by engineering judgement, analysis of the required activities, survey of the available means to meet the requirements, and reference to similar situations in other systems. Once the relationship has been established, the basic assumptions can be tested and the decisions resulting from those assumptions validated or modified.

COMMAND QUANTIFICATION

A determination of the required frequency of each command type originating from the RCS is required to develop an optimal configuration of means. An effects analysis is suggested to solve the problem of command classification, i.e., determine the effect of command errors for each type of command identified in this study. A determination of the number of commands expected for the control of each spacecraft function, the frequency[1] with which they are expected to occur, and those requiring management review and approval can be obtained by a command count (1) after the effects analysis has been performed and (2) after an estimate on the decision and execution times within the RCS has been made. The resultant quantitative data will better enable the designer to determine the number of control positions, the number of personnel required to man them, and the expected load on project management in the review and approval function.

[1] The frequency of produced commands depends upon the type of processes that are required and the means provided to meet the requirements.

RCS TIME DELAY QUANTIFICATION

Each process or action within the Remote Control Station consumes time. An assumption made in deriving the design concept was that the quantity of fast response situations required the use of automatic systems within the RCS, such as a command-retrieval system. This assumption may be invalid if the time involved in review, validation, and other quality control measures is significantly greater than the time savings resulting from automation. Also, the assumption was made that the level of automation suggested by the design concept would reduce error probabilities, decreasing the time required for quality control. These assumptions require testing.

The total elapsed time from data input to command output can be estimated by listing all of the processes, actions, and decisions that must occur; determining which are in sequence and which are in parallel, and the means available to perform the functions; and generating the range of time values expected based on best judgment. This judgment can be enhanced by referring to experiences in similar circumstances, observing and interpreting time values from ongoing JPL activities, and, if necessary, conducting a small research project. The results of such a project should help establish (1) which functions, activities, and tasks are time sensitive, (2) quantitative values and the variance of performance times for these functions for the most promising concepts, and (3) provide time data to be used in a time-reliability trade-off analysis. A formal research effort would be justified if (1) the desired results are not available from other sources, (2) the desired results significantly affect design decisions, and (3) the research effort costs less than the potential design error. The resulting data will help establish which means should be selected, the loading and distribution of loads in the RCS, and will indicate a relationship between particular RCS means and concepts and response times. It is anticipated that various design decisions, if implemented, would result in different minimum response times. Such data are desired prior to design implementation.

RELIABILITY QUANTIFICATION

Although the effect of errors can usually be predicted, the probability of an error occurring within the Remote Control Station is quite difficult to predict during design conceptualization. A basic assumption made when selecting and allocating general means to particular functions was that the inherent reliability of the RCS was essentially time dependent; i.e., any arbitrarily selected reliability value could be obtained if sufficient time was allowed during the subject process. Although this is not strictly true, particularly in processes involving human judgment, the assumption establishes that a relationship exists between time and reliability. It was also assumed that the probability for error within the RCS was sufficiently high to require quality control measures. Commands requiring extensive time-comsuming quality-control measures were assumed to be the slow response type; whereas, those requiring the least quality-control time were assumed to be the fast response commands. These assumptions impact the activity flow within the RCS and the means required to implement the function. Therefore, they must be tested.

A time-reliability relationship, for given means selections, is desired for further design studies. It may be based on data collected on the reliability of man and machine performances in situations similar to those expected to occur within the RCS. Projecting and evaluating the variation in performance reliability in accelerated or retarded times as well as increased and decreased work-load conditions should provide a reference for developing a reliability model of the Remote Control Station prior to design implementation.

COST QUANTIFICATION

Many times a designer is instructed to conceive a system without regard to its monetary costs. Usually, that freedom is curtailed during system development and procurement. If a monetary constraint is imposed, the basic concept may have to be altered. It then behooves the systems designer to be able to relate system costs and performance to defend a higher cost system if necessary, or, conversely, to avoid unnecessary expenditures when performance is not enhanced or is not critical to the system output. Data on the means costs of the system are therefore needed. A tabulation of the candidate means with their capabilities and their costs will permit valid trade-offs to be conducted. Other factors to consider in such an analysis are the impact that candidate means may have on peripheral systems. For example, if a selected concept that meets both cost and performance specifications propagates increased costs or decreased performance in interfacing systems, those changes must be included in the trade-off. In the design concept presented in this study, no specific constraints were placed on costs. The costs to implement the design were not estimated; however, they appear to be reasonable. Implementation of the selected means concepts is considered to be well within the current state of technology.

QUANTIFICATION OF RCS EFFECTIVENESS

The Remote Control Station, together with the adjacent systems, should be assessed for effectiveness. Since many design decisions inherent in the design concept influence one or more of the factors contributing to effectiveness, a quantitative determination of this measure is needed to determine (1) the potential effectiveness of the design concept and (2) areas of improvement. One technique to quantify effectiveness has been presented in chapter II by means of a digital-computer simulation model.

The purpose of this chapter is to present the conclusions inferred or derived from the study and recommend steps which will allow the results of the study to date to be carried to a point of fruition. The conclusions are based not only on the study results themselves, but also on the application of Serendipity's systems-analysis technique.

CONCLUSIONS

1. A conceptual design of a Remote Control Station (RCS) system can be developed which conceivably can control future unmanned spacecraft systems even if the design of these systems is not definitive. The adequacy of the design depends, however, upon the adequacy of spacecraft systems analysis. If the spacecraft systems analysis has successfully defined the major spacecraft performance variables, the conceptual design of the RCS should be adequate.

2. The major changes of states in the RCS occur in the Assess Situation and Determine Course of Action functions. The complexity of these functions depends on both the predicability of the initiating state and the required state, given the initiating state.

3. A considerable number of RCS control functions (subfunctions of the Assess and Determine Course of Action function require the same information. This sharing can be handled either by common displays, or by different displays driven by common software, depending on the criticality of the information.

4. Control types I and II are highly amenable to automation, or automation under manual control. These controls also lend themselves to local-option decision control which reduces the integration load and, in turn, decreases the response time.

5. The spacecraft systems that the RCS must be able to control have not been defined to the extent where specific responses to spacecraft mechanism state changes can be defined. Furthermore, even if these were defined at this time, the likelihood that design changes would occur before and during the lifetime of the RCS is very high. An effective RCS must be able to account for these modifications without having to undergo time-consuming and/or expensive modifications. The most suitable RCS design appears to be one based upon mission-independent hardware driven by mission-dependent software. Such an approach should result in minimum reconfiguration of hardware from mission to mission, since most of the reconfiguration could be handled by changes in computer programs. This concept may uncover other design problems in the areas of standardized displays and controls, modular arrangement of hardware, and configuration control of computer programs.

6. The conceptual design was defined to the level of work stations, functional responsibilities, and block schematics. A more detailed design was not possible primarily because there was neither sufficient time nor manpower to accomplish this. The next lower level of design details could have been provided (but this was not advisable) if sufficient time and manpower had been available to develop a comprehensive list of candidates of spacecraft mechanisms which could be categorized into groups requiring similar displays and commands.

7. The modular aspect of the conceptual design will accommodate multiple missions simultaneously. The extent to which additional consoles will be needed is a function of mission priorities and similarity of parameters between the missions. Simultaneous missions may require additional hierarchies in the organizational structure if the load becomes excessive.

8. The RCS functional configuration is based on the assumption that the reliability of command sequences as generated (or modified) will be sufficiently less than unity so that check functions will be required. If this assumption is not valid, and if the check function is not highly reliable, there is a possibility that the check

functions may increase the system reaction time without significantly improving the overall system reliability.

9. Integrated control is possible with an organizational structure consisting of no more than three levels in the hierarchy. Additional levels may be required if simultaneous missions are conducted and the load is greater than can be handled by the top level. The experimenters should be the lead controllers. Integration between the experimenters and the support-function controllers becomes necessary only in the event of conflicts. Conflicts can then be resolved by the next higher level. Usually, the support functions are required to support the experimenters. "Unreasonable" requests can be resolved by the next higher level.

10. The basic requirement for the higher levels in the organizational hierarchy is to continually update the mission plan, assign priorities, interface with higher-level management in the overall system, and review critical decisions.

11. Critical decisions regarding man-machine allocations were made possible by classifying control situations into types I, II, and III. These decisions were independent of personnel type, rather, they were based on the general capabilities of men and computers. Multiple man-machine allocation decisions will be required at the next lower level of design.

12. Man is the basic decision maker; however, he is aided by the computer, which recommends actions and checks the reasonableness of his decisions.

13. Attempts to arbitrarily classify the time dimension into real time, near-real time, and non-real time, etc., do not appear to define adequately the boundaries of a "fast response" RCS system. The important factor appears to be the time delay allowed between the occurrence of an event and the reaction to that occurrence, and the time delays necessitated by physical law, such as the time required to transmit the information from the spacecraft to Earth and vice versa. These are the time factors which are critical to the design of the remote control station. Whether these delays are classified under any category of real time is not important for analysis and design purposes.

14. The ultimate design of the RCS cannot be fixed until quantitative requirements have been established and met, and the relationships between the performance elements in the system and the system criteria have been established and quantified. Means allocated on a qualitative basis will not necessarily meet the quantitative requirements. The current design concept of the RCS is based primarily on qualitative requirements. Its "worth" cannot be proven at this time. Furthermore, selection of a set of specific means cannot be justified at this time due to the lack of quantitative data concerning the extent to which the means contribute to system performance.

15. A digital simulation model is considered to be the most effective means for obtaining quantitative data and establishing quantitative relationships, because of the large amount of interactions involved in this system. The performance of specific functions or means within the RCS are dependent not only upon the performance or related functions and means, but also upon variations of noncontrollable elements, such as environmental conditions and performances within adjacent, interfacing systems such as the SFOF. Delays on the order of minutes in the adjacent systems may not make it worthwhile to attempt to improve response times in the RCS. Therefore, although more detailed design is possible at this time, it would not be worthwhile until quantitative requirements and relationships are defined.

16. Serendipity's systems-analysis technique was generally applicable to the project. Application of the technique in this study identified the need for one major modification and one major weakness.

    a. The technique, as previously stated, required assessment of system effectiveness after the initial conceptual (physical) design was completed. Experience on this study, as well as other recent studies, indicates that quantitative requirements and relationships can and should be defined (1) after the initial functional configuration is developed, and (2) before the initial conceptual design is developed. The quantitative data will aid the designer in allocating means, relying less on judgment and experience.

b. The major weakness in Serendipity's technique is the scarcity of guidelines for conducting static synthesis of analytical data. The lack of such guidelines resulted in premature design conceptualization which had to be modified after the data were properly synthesized. More attention must be given both to proper synthesis of analytical data and to development of tools to aid in this synthesis.

c. The technique provided highly useful guidelines for analyzing the systems; however (1) did not prevent the analysts from delving into "blind alleys," (2) it is difficult to communicate unless the receiver is experienced in systems-analysis problems the technique is designed to meet, and (3) it must be applied at all levels of analysis if the results are to reflect the analysis.

17. To develop a conceptual design within the time and cost constraints of the study, it was necessary to assume means constraints which appeared to be realistic and practical. Artificial constraints can stultify creative design but to proceed without any constraints is not practical either, since the project still had to be completed within the specified budget and schedule. However, the lack of means constraints by JPL allowed us to assume constraints as they were deemed necessary to properly scope the project. Generally, the reasonableness of the assumed constraints could be checked quite easily.

18. A sufficient quantity of relevant research data was not readily available to allow personnel allocated to the task to develop design principles useful to the study. It is not known whether such principles can be developed now that the requirements for the RCS have been defined.

19. The original program plan, to include both the (1) development of a system-effectiveness tool and (2) application of the tool to assess the system effectiveness of the conceptual design, was overly optimistic. The tool cannot be developed until the functional configuration is defined. The functional configuration of the RCS could not be properly defined until the spacecraft states were analyzed properly. Analysis of the spacecraft states consumed approximately twice as much manpower as we had originally planned due to lack of definition of the candidate spacecraft systems and the need to synthesize available data on the spacecraft systems.

RECOMMENDATIONS

The recommendations in this section are limited to those considered to be necessary to assess the adequacy or effectiveness of the RCS conceptual design presented in this report. Recommendations beyond the scope of logical extension of the current study are not presented since they would appear presumptuous and not adequately justified.

1. Quantitative Analysis of the RCS Conceptual Design

It is recommended that the digital simulation model discussed in chapter II be developed and used to (1) assess the relative effectiveness of the conceptual design presented in chapter III, and (2) develop quantitative relationships between system-performance criteria and accountable factors. The independent variables for the study should be:

a. Performance times for all RCS functions
b. Functional reliability for all RCS functions
c. Spacecraft compositions
d. Data-collection objective priorities
e. Delay times in adjacent systems

The study can be conducted without data on current operations, but final interpretations and a more efficient study can be conducted if a reasonable range of a, b, and e are established on the basis of current operations. Therefore, part of this study should include analyzing (and collecting, if necessary) time and reliability data on current SFOF operations similar to the functions in the RCS.

Whether reliability data can be obtained on current SFOF operations depends on the manner in which data have been and/or can be collected. In the event that functional reliability of current operations cannot be assessed, it is recommended that a reasonable range of values for study be based on data available in public literature. Specific studies to obtain such data should be withheld until the sensitivity of the system to functional reliability is established.

Reasonable ranges of values for c and d can be established by a committee of JPL scientists and engineers. Priorities may be difficult to establish, but the only requirement for the priorities is to have a representative sample of priority schemes.

It will also be necessary to relate RCS mean classes to the accountable factors to estimate the contribution of the specific conceptual design to system effectiveness. This effort should also aid in identifying areas which should be examined in greater detail.

2. Effectiveness Analysis of Programmed Display/Control Concept

It is recommended that an investigation of the feasibility of a mission-independent hardware/mission-dependent software design concept be conducted, concurrent with 1 above. The effectiveness of this concept, in terms of cost, response time, reliability, growth potential, and flexibility, should be the basic objective of the study. Since this approach appears to offer great promise in display/control flexibility, it merits a detailed analysis. The analysis should assess the required computer capacities, the programming loads, and the times and costs necessary for implementation of selected control functions as well as for total control of the spacecraft system. The implications on current and planned computational facilities, in terms of cost and flexibility, should be determined considering the acquisition, installation, and checkout of peripheral equipment compatible with the existing or planned computational system. Similarly, the cost effectiveness of acquiring new equipment should be determined. This recommended study consists essentially of two major efforts:

a. Analysis of JPL data-processing requirements and capabilities, and the impact of an integrated, generalized computer-driven display/control concept.

b. A detailed study of the state of the computer-driven display and standard display technology (cost versus capability).

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The approach used in this project may be classified as a system engineering approach. The purpose of this chapter is to describe that approach and the underlying concepts to provide some insight into the reasons for some of the results presented in the report. The description is not intended to serve as a "cookbook" nor a procedure for system engineering which can be applied to other projects. We have neither the time nor the capability to provide such a document. We have, on occasion, procedurized certain portions of the system-engineering process for specific projects, especially when a large number of analysts are involved. However, these procedures are seldom found to be adequate for other projects because of their specificity.

The approach is explained in terms of underlying concepts and ground rules for applying the concepts. The description does not cover every step taken in the project nor does it attempt to explain every product. However, an attempt is made to explain the ground rules in sufficient detail to allow the reader to reconstruct the major steps if this is deemed necessary. It is highly doubtful that the total process can be reconstructed on the basis of the concepts and ground rules alone. It is also doubtful that the reader will be able to implement the approach presented in this chapter on the basis of the concepts and ground rules alone. There is still a considerable amount of "art" involved in the system engineering process. Concepts and ground rules such as those presented in this chapter help to structure the approach. The quality of the output, however, is still dependent on the capability and experience of project personnel.

The set of concepts used in the project and described in this chapter was developed over a period of years by various individuals currently associated with Serendipity. The concepts are not necessarily unique nor universally accepted. However, they have proven to be quite useful in the analysis of widely diversified systems. The set is a dynamic one in that it has been continually expanded or modified, depending upon the experience gained with each problem to which the concepts have been applied. Thus, the set of concepts presented in this report differs somewhat from the set presented in previous efforts to document the concept. Similarly, the set will very possibly differ somewhat in subsequent reports. Over a period of approximately eight years, the major changes have been in expansion of the set, more formalization, and additional details.

ASSUMPTIONS UNDERLYING THE CONCEPTS

Our concepts were developed because of certain assumptions we have made about the system-engineering process. These assumptions are not critical to the validity of the concepts, but they are important to the usefulness of the concepts.

Assumption 1

Most systems developed under the auspices of the United States Government are too complex for any one individual to adequately consider all the relevant materials. This assumption indicates the need for some means of partitioning the system into manageable elements.

Assumption 2

A significant portion of any new system is comprised of resources developed and/or used in older systems. Thus, a new system may be created, but it is usually comprised of many old parts. Only a portion of the design process requires creativity and the rest of the process involves finding new uses for existing parts. This assumption also suggests a need for partitioning, but for the purpose of determining whether creation or reassignment is required.

Assumption 3

The manner in which a problem or requirement is presented affects the solution. Too frequently solutions are sought without an adequate definition of the problem. Similarly, systems analysis is frequently initiated with a preconceived notion of the design which usually results in the analysis being biased by the preconceived design.

The strong emphasis on requirements orientation in the approach is based on this assumption.

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Documentation per se does not represent objective analysis. It does make it simpler to detect biases, but this advantage can be diluted considerably if the reviewers are inundated with data.

Assumption 4

Creation per se is not adequate for a specified system. The value or merit of the created design must be measured in terms of the extent to which it contributes to meeting the requirements in relation to its cost. A new creation is not useful if it does not meet the requirements. This assumption, plus the partitioning, indicates the need for some method of synthesizing the parts and measuring the totality.

Assumption 5

Some order or structure must be introduced into the design process if it is to be accomplished within time and cost limits. The structure should not restrict the creative aspects of the design process, but rather should enhance them. This assumption indicates the need for clearly defining requirements in non-means terms which will allow the designer the freedom to search for and/or create the designs without restricting his search or creation by preconceived designs.

SOME USEFUL CONCEPTS

A detailed search of system-engineering literature indicates that very little public information is available on concepts underlying system engineering. Voluminous materials are available on (1) the advantages of system engineering, (2) procedures for implementing portions of the process, and (3) techniques applicable to specific aspects of the total process. This chapter is not intended to fill the conceptual void. The concepts are presented merely to explain the approach used in the project. The concepts may not coincide with what others regard as those underlying system engineering. The compatibility of the concepts discussed here with other concepts can be determined when the other concepts are made public.

THE STATE-CHANGE CONCEPT

A state may be defined as a set of qualities which describes a form of existence of any aspect of the universe. A state can be expressed with any symbol or words which reflect qualities of the real world and can be quantified. Any two states of the same class define a performance entity if the time for the states differs and if one or more of the qualities comprising one set differs in value or type from the qualities comprising the second set. In such a case, the state occurring first is termed input state and the state occurring last is termed output state.

A system is a set of performance entities which act in concert to change an input state to an output state, within established constraints. A system can be a performance entity. The definitions of state and system indicate that anything can be treated as a performance entity so long as the input and output states can be defined. Conversely, to define a performance entity one must first define the input and output states. This is the state-change concept. The name attached to the entity is not important technically, although it may be for communication purposes. Generic terms frequently used for the entities are system, subsystem, function, activity, and task. Generally speaking, these differ in terms of the complexity of performance required for transition from the input state to the output state. The process of specifying states to define requirements may appear simple and straightforward, but generally it is not. Let us examine some sample differences in requirement statements when the state-change concept is used.

The basic requirement for a weapon system is generally some state of destruct of enemy targets, or an active enemy weapon system in a passive state, usually as a result of our system serving as a deterrent. In order to properly define the requirements, it is necessary to specify both the set of qualities which define the operational state of the enemy targets and the set of qualities which define the destruct state. System specifications frequently contain statements covering speed, payload, etc. These, however, are not requirements at the overall system level according to the state-change concept. They are constraints (necessary though they may be) in that someone has already made a decision on the size of the payload (means) and the reaction time which will be necessary to achieve a certain level of destruct state of enemy targets. However, these same parameters may be a requirement for a function(s) within the system.

The basic requirement for a checkout function is to change the state of knowledge or information. An equipment item enters a checkout function in a given state (good or bad) and leaves the function in the same state. The only state change required of the function is information or knowledge on the true condition of the equipment item. Furthermore, in order to properly define the requirements for the function, it is necessary to define the various "No Go" or bad conditions the equipment item might be in and about which information is required.

Similarly, the requirement for a "check" function in the RCS is a knowledge state regarding the quality condition of command sequences. The "check" function does not change the state of the command sequences. In other words, the actual state of the command sequences remains the same. However, the knowledge state regarding the quality of the command sequences is either zero or less than some specified value. The requirement for the function is to increase the knowledge to the specified level. In order to accomplish the necessary change of state, it will probably be necessary to obtain some measurements which can provide the necessary information to advance the knowledge state to the required level.

In the same manner, the basic requirement for the total data-collection system is to advance the state of knowledge of certain properties of the Moon, Mars, and/or Venus. The basic state-change requirement is not to collect data, or to control spacecraft locations. These are performances required to advance the knowledge state. In this study, it is assumed that achieving certain data states will allow achievement of required knowledge states.

Proper definition of the states is extremely critical to the state-change concept. Unless the states are defined, analysts will frequently use familiar names to identify a function (or block within a functional-flow block diagram) without first determining the requirement for the block of function. More important, the blocks tend to become "gospel" because they are functions, not equipment, and therefore are assumed to be valid. Unfortunately, many functions are frequently created to fit a preconceived design. The aforementioned checkout function is a good example. Almost every existing maintenance system has a multitude of checkout functions. This does not necessarily mean that every system should have all these checkout functions. If the increase in information state is not significant, one must seriously question the utility of a checkout function. This also applies to the check function included in the RCS FFLD in figure 2-14. For example, it may be possible to design a method formulating command sequences so reliable that the probablity of an error is reduced to .0001. The check process itself may erroneously reject good command sequences which could degrade the overall system performance.

THE SYSTEM HIERARCHY CONCEPT

A system rarely exists by itself. It is generally a part of a larger system and interacts with other systems which may or may not be a part of the same larger system. The larger system of which the system of concern is a part is termed the supersystem. The system of primary concern is termed the reference system. This is the system to be developed. The system acted upon directly by the reference system is termed the object system. Usually, the primary objective of the reference system is to effect a change of state in the object system.

Any other system (besides the object system) which affects, or is affected by, the reference system is termed an adjacent system. An adjacent system which affects the reference system either contributes to one or more of the qualities comprising the input state for the reference system, or imposes a constraint on the reference system. An adjacent system affected by the reference system either receives an input from the reference system (desired or adverse) or is constrained by the reference system.

The relationship is not always easy to identify. However, it is important to establish the relationships as early as possible in order to clearly identify the boundaries of the reference system. Boundaries not clearly defined at the outset are apt to return to haunt you.

In most cases, the object system will have to be analyzed in detail to define the requirements for the reference system. Failure to do this has created considerable problems in development programs in the past. In the current project, the object system is a generic unmanned spacecraft system, whose objective is to collect specified scientific data at the moon and selected planets. The reference system is the Remote Control Station (RCS) system. Examples of adjacent systems are the Deep Space Instrumentation Facility (DSIF) system, portions of the Space Flight Operational Facility (SFOF), and the JPL personnel system.

The basic purpose of figure 2-3 in chapter II was to help establish the boundaries of the component systems and the relationships between the systems. Although the states were expressed in relatively gross terms, they served to establish the basic responsibilities for the various systems. For example, the only data transmission responsibility for the RCS is whatever transmission is necessary to locate the commands at the place and in the necessary form where the SFOF can take over.

An important delineation was establishing the boundaries of the spacecraft system. The DSIF and SFOF systems were treated as constraints for the study. Although interfaces with the DSIF/SFOF could have a significant effect on both the total system and RCS operations, they do not establish requirements for the RCS, the reference system. Therefore, analyzing them would not be fruitful at this time. On the other hand, the spacecraft system, which is the object system for the RCS, had to be analyzed to establish the basic requirements for the RCS. The boundaries established in figure 2-3 helped to prevent confusion on whether to include specific aspects of the DSIF and SFOF in the analysis of the spacecraft system and the RCS system.

THE CONCEPT OF REQUIREMENTS PRECEDING MEANS

Means may be defined as a process of effecting the transition of an input state to an output state. It is important to note that means may be either functional or physical. Physical means (e.g., man, computer, technical manuals) are required to implement functional means (e.g., calculate, detect, display). Generally, there are alternate physical means to implement a given functional means, and alternate functional means to implement a given state change required. In systems engineering, settling on physical means before identifying the functional means can restrict the creative aspect of the design process. However, we should recognize that the functions also represent a level of means, albeit not as specific as physical means.

In recent years (especially with the advent of the AFSCM 375-5 document), considerable attention has been given to establishing the functional requirements before settling on hardware, personnel, displays, procedures, etc. It should be pointed out that the power of this approach will be lost if the functions are defined in an arbitrary manner. There must be an underlying reason for delineating functions. We have found that partitioning the system into smaller units of state changes within the system helps considerably in conducting an objective functions analysis. It is important to keep in mind that functions analysis and other similar analyses are conducted primarily to provide the system engineer a base for selecting a <u>set of physical means</u> which will best meet the requirements within the time and cost constraints. Some of these means may have to be created. Most of the means are probably in existence but will have to be found.

As indicated previously, no new system is designed to exist in a vacuum. In fact, one might regard any new system as essentially an evolution from some existing system or systems. Even in the current study where constraints were not stated explicitly, the RCS is still an evolution of certain aspects of the SFOF currently in operation. For example, the SURVEYOR flights are controlled by the current version of an RCS, although it is not termed an RCS. Certain means are generally established as constraints at the outset. For example, JPL personnel with certain performance characteristics and the JPL computer complex probably are realistic constraints for the RCS. Constraints are defined as limits placed on the freedom of selecting means (functional or physical) for a system or any portion thereof. Establishing means as a constraint is a very tricky business. Frequently, one has to establish constraints to take advantage of experience gained in similar systems. Somewhat paradoxically, preestablished means tend to limit the search for new and perhaps better means during the development process.

It should be noted that constraints are generally necessary "evils" in a development program if the program has a time or cash limitation. This is especially true when constraints exist regardless of whether they are stated. Decision making in a situation where infinite degrees of freedom exist can be an extremely lengthy process. To properly scope the effect, it is frequently necessary to identify practical constraints, i.e., constraints which probably could not be overcome within the time period of the study, or the lifetime of the system.

Examples of such constraints assumed for this study are the existing SFOF/DSIF, JPL personnel, the JPL computer complex, some of JPL's current methods of checking the compatibility of command signals, and JPL's data-processing means.

The need for constraints to establish some limits on the alternatives to consider is probably one of the greatest traps associated with constraints. There is a gray area of judgment involved in determining whether a means constraint is necessary to limit the scope to a practical level, or whether a set of means is erroneously selected before the requirements are firmly established. Requirement statements tend to be somewhat abstract whereas means are relatively concrete. Therefore, the general tendency seems to be to gravitate towards a specific set of means, even when generating requirement statements.

THE SYSTEM-EFFECTIVENESS CONCEPT

The output state of a given system is usually a set of qualities, each of which can be regarded as objectives. System effectiveness is a measure of how well these objectives are met and the extent to which elements within the system contribute to the effectiveness. These elements are generally termed "accountable factors." In certain cases, a meaningful definition of system effectiveness cannot be accomplished unless the supersystem is considered. In the current study, the criteria measures for system effectiveness are related to the output states of the spacecraft systems (scientific data) rather than the output states of the RCS system.

According to the system-effectiveness concept, the relative value of an element within the system is determined by the extent to which it contributes to overall system performance. This allows trade studies by comparing the relative contributions to system performance with the relative costs involved. This also requires every major element in the system to be expressed in terms meaningful to the overall system performance.

Applying the system-effectiveness concept is not a simple task. There is generally a high degree of interaction between elements within a system which makes it quite difficult to isolate the extent to which a given element, such as a set of displays or an individual situation assessor, contributes to system performance. The relative effectiveness of a specific portion of the RCS system can be evaluated only in terms of how well it supports the object system in collecting useful scientific data. However, the effective performance of the selected portion is dependent on other variables as well, such as the DSIF, environmental conditions, organization of mission personnel, other elements in the RCS system, etc. The problem is one of partitioning out the other effects such that the effect of the portion of concern can be considered above and beyond the fluctuations caused by the other variables. Although this is not simple, it can and has been done.

System effectiveness is a concept that has gained considerable popularity in recent years, both in government and in industry. Relatively successful operations have been noted in various projects. However, widespread application in daily design activities is still not a reality. To implement the concept at the detailed design level, useful techniques must be provided and the engineers must accept the approach as a useful one. Neither the technique nor acceptance is a reality yet. However, advancements in the development of techniques and increased interest by top management and government agencies indicate that the concept will soon be implemented in all major development programs.

The major difficulty in implementing this concept appears to be in relating detailed accountable factors to system-effectiveness criteria. Interaction between accountable factors is the rule rather than the exception in most complex systems. For example, delay time in responding to spacecraft state changes interact with performance reliability in that errors affect the delay time and time stress tends to decrease reliability when personnel are involved. The two factors also interact with planet and spacecraft conditions which determine the demands placed upon the RCS.

Despite the difficulties, techniques are available at least to implement the concept in part. The alternative is to suboptimize or to bank on engineering judgment which cannot be validated until a relatively expensive model is available.

CONCEPTS OF ANALYSIS AND SYNTHESIS

Analysis is a process of partitioning a system into smaller performance entities, and synthesis is the reverse process of combining the performance entities within a system to form a set. A mathematical analogy to analysis and synthesis is differential and integral calculus. Functions analysis is the generally accepted process of partitioning the system into smaller elements. The process can be applied to the object system as well as to the reference system, but the level of difficulty is considerably higher for the latter than for the former. In the case of the object system, the system already exists and the process is primarily one of reviewing and documenting the functions. In the case of the reference system, the functions analysis represents the first-cut at defining the elements of the system. Each function defined becomes a part of the system for which some physical means will be assigned (or designed).

There is no generally accepted method of synthesizing the elements. Many designers depend on the capability and experience of groups assigned the responsibility for physical subsystems, e.g., computer subsystem, power subsystem, personnel subsystem, technical manuals, etc. Some have developed computer programs to simulate the system and/or to process the data to identify common requirements factors. Others simply ignore the data and conduct business the way they always have, regardless of the specific requirements for the system.

It is generally true that the synthesis job is relegated to the means specialists or the people responsible for developing the means to meet the requirements. This is understandable since the requirements for any given class of means will be scattered throughout many different functions. The results of the analysis will not be of any significant use unless they are synthesized and used by the means specialists. Data per se have no intrinsic value in system engineering. They must be used and/or found useful by the recipients of the data.

Considerable attention has been given to the development of tools to aid in analysis. Surprisingly little attention has been given to the development of tools to aid in synthesis. The lack of such tools has frequently negated the potential utility of analytical data. The decision makers, or designers, are frequently inundated with unsynthesized data and, in many cases, ignore the data and base their decisions on judgment.

Problems of improper synthesis were noted in this study, both in terms of communicating with JPL personnel and in terms of attempting to base the design on a large set of unsynthesized, analytical data. Properly synthesizing the data provided a significant improvement in relating design to the requirements. The function-by-function and function-by-information requirements matrices are examples of synthesized data.

One of the major contributing factors to improper synthesis is the lack of recognition of its importance or the man-hours required to synthesize data. Frequently, personnel providing the data assume that the data will communicate the necessary information without any synthesizing activity. This is frequently the case when the analysis is conducted by a computer. More often than not, the outputs are a large stack of computer printouts which requires many man-hours of interpretation if information is to be obtained from the printouts.

Proper synthesis is important throughout the total system-design process. In this study, the two most difficult synthesis tasks occurred before analysis could be initiated. These documents covered the entire spectrum of the total system and were supplemented by discussions with JPL personnel. There is no concrete set of data that we can point to as the direct product of this synthesis activity. Yet, the spacecraft state-change analysis could not have been completed without first synthesizing the available data. The difference between synthesized and unsynthesized data is somewhat on the order of the amount of information presented by the mean and variance for a distribution compared to the amount of information conveyed by hundreds of pages of numbers without the mean and variance prepared.

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CONCEPT OF THE REQUIREMENTS-ORIENTED DESIGN PYRAMID

A requirements-oriented design pyramid is presented in figure 5-1. This pyramid represents an order, or structuring, of the major processes involved in design or system engineering. The pyramid has an abstract system bound only by its requirements at the apex, and the detailed representation of both the functional and physical means of the system at the base. In between, the analysis, synthesis, and design conceptualization processes recur at varying levels of detail.

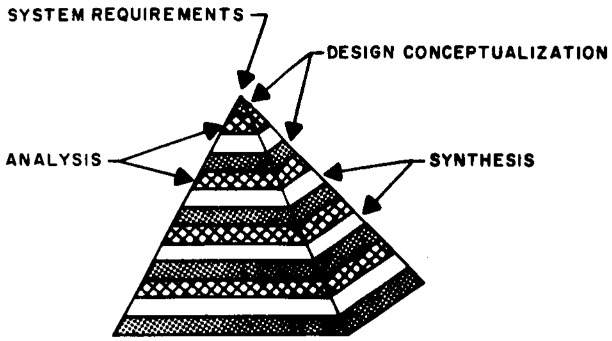

Figure 5-1. Requirements-oriented design pyramid.

Design conceptualization is the process of establishing a design concept and represents the most creative aspect of the total system-engineering process. Inputs to this process are requirements, higher-level constraints, and the design concept established at the next higher level.

The so-called data proliferation results from the implementation of this design pyramid. The first level of analysis may result in say ten major functions. Each of the ten functions at the next level of analysis may be partitioned into ten lower-level functions, resulting in one hundred functions. If each of the second-level functions are partitioned into an average of five lower-level functions, we have five hundred functions at the third level of analysis. It is easy to see how the proliferation takes place.

As a result of this proliferation, it is important that synthesis also be conducted at varying levels of detail. Furthermore, the analysis or partitioning at any given level must be compatible with the design concept established at the next higher level. Unless attention is given to maintaining compatibility at varying levels of detail, the basic power of the system-engineering process can be lost, since the physical system is at the base of the pyramid. If decisions are made at the base independent of decisions made higher up in the pyramid, the value of partitioning the system into smaller and smaller elements and allowing specialists to examine each of these elements will be lost. The end product will be strictly a function of the decisions made at the lowest level of detail.

To maintain this compatibility, it is important that synthesis be accomplished at manageable levels. Experience has shown that analysis, or partitioning, is more effective if it is accomplished at varying levels of detail. We have learned from experience and can assume that synthesis will be simpler if we synthesize at varying levels of detail also. For example, it is simpler to synthesize ten sets of data comprised of one thousand common elements each than to synthesize all ten thousand elements at once.

The design pyramid also indicates that decisions made closer to the apex of the pyramid will have greater effect on the final system than decisions made at the lower level of the pyramid, so long as the decisions are implemented throughout the pyramid. This implies that means specialists will have to provide their inputs to the system decision makers early in the development life cycle if they are to have any major impact.

It is well to repeat that the design-pyramid concept results in the same basic techniques applied in an iterative manner at varying levels of detail. The difficulty in applying the techniques decreases as the level approaches the base of the pyramid as a result of the constraints established at higher levels of design conceptualization. These constraints provide a structure or framework which limits freedom of choice, thereby making the system less abstract and, therefore, easier to handle. This also means that decisions at higher levels of the pyramid are extremely important because they tend to constrain selection of means at lower levels. By the same token, these higher-level decisions are more difficult to make because a structure has not yet been established.

Cost studies have shown that a significant portion of development costs results from poor or premature decisions made at higher levels of the pyramid. These decisions result in modifications which require a considerable amount of work to be redone. It is doubtful that such modifications can ever be eliminated. However, it should be possible to reduce the frequency and magnitude of these changes by more careful analysis at the outset, and proper design-disclosure formats which show clearly the relationship between system elements.

THE CONCEPT OF FUNCTIONS SERVING AS BUILDING BLOCKS

It is fairly well established at this time that functions serve as the basic building blocks of the system. The varying levels of partitioning exemplified in the design pyramid results from partitioning functions into lower-level functions. Many of these functions depend upon means decisions made at the next higher level. Within that decision, however, the next level of partitioning still is kept relatively free of additional means. For example, a decision to use a computer as a means of processing data will require further partitioning for functions specific to a computer such as data preparation, inputting data, etc. However, the partitioning is not based on a priori decisions on how to accomplish the functions within a computer.

Means are assigned to the functions both individually and as a group. Groups of functions, however, are usually assigned to means specialists, depending on the class of functions involved. Many means specialists, such as those responsible for personnel subsystems, will receive a diverse group of functions because personnel are needed in many different functions. This makes it more difficult not only to synthesize the requirements, but also to relate these types of means to overall system performance.

GROUND RULES

The first set of ground rules are those relevant to establishing the boundaries of the system. In many cases these boundaries are preestablished and do not require definition within the project. The subsequent sets cover the application of specific techniques throughout the pyramid.

ESTABLISHING SYSTEM REQUIREMENTS

Establishing the Boundaries for the Supersystem

Establishing boundaries for the supersystem is not a simple task. It is difficult to establish clear-cut guidelines on how to go about defining the boundaries for all projects since each project differs in terms of available information. The following ground rules were found useful for the current project but may not be useful to other projects.

Ground Rule 1:

Identify the input and output states. This establishes the objective, but provides no guidance on how to go about identifying the states.

Ground Rule 2:

Define the class in which the output state is a member. The easiest way to identify the output state is to obtain first a general idea of the object system and examine its mission objectives. These objectives will provide an indication of the class of states involved. For example, objectives for scientific missions are usually expressed in terms of data. This implies that the output state of the supersystem belongs in the class of knowledge or information. The general system diagram in figure 2-1 established the basic state class as knowledge or information about planet states.

Ground Rule 3:

Define the class in which the input state is a member. A hint as to the class of the input state can be gained by noting the class of the output state. In the case of the above sample output state, the information must be about some object. In the case of scientific space missions, the object is probably some set of planets on which information is not now available. This type of information usually will have to be obtained from mission planners or descriptions of missions. The diagram in figure 2-1 also established the spacecraft as a state class, although the spacecraft is not specified as an output state class. This is frequently useful when means constraints for the supersystem are known. In this study, spacecraft systems were the specified data collectors and were to be the object system. Thus, it was useful to establish the spacecraft as a class. In addition, specifying the location of the spacecraft also required location to be treated as a state class. For

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example, specifying Earth as the location meant that change of location to the planets had to be accomplished within the system.

Ground Rule 4:

Establish the subclasses of the input state first and use these subclasses to determine the corresponding output state subclasses. Once the class of both the input and output states has been defined, it will be necessary to define all the subclasses relevant to the supersystem. The extent to which the class should be divided is judgmental in most cases. Theoretically, one should partition the states to the lowest level necessary to identify all of the parameters essential for properly defining (i.e., quantifying) the states. However, there are many cases when the objectives have not been sufficiently defined to allow such a thorough analysis of the states. Such was the case in the current project, since all the relevant missions have not yet been defined. Furthermore, many systems development/analysis projects are initiated under the assumption that the objectives have already been defined sufficiently. Under these circumstances, there is usually not sufficient time to thoroughly analyze the states.

The question is how thorough should be analysis be if the objectives are not specified in detail. The level of detail to which the analysis should be carried depends to a large extent on the nature of the reference system, its relation to the object system, and the level to which the reference system is to be conceptualized. In the current study, the analysis was only carried to the point where reasonably acceptable subclasses were identified. The supersystem bounded by these subclasses was greater in scope than the spacecraft systems envisioned for the next five to ten years. Further analysis was not justified since additional classifications would not help to further define the supersystem, and considerable resources would have been required. The classification of data-collection objectives presented in table 2-2 represents the subclasses of the planet-state class input in figure 2-1. These state subclasses also define the information-state subclasses since they are tied to the planet states. Although the subclasses are fairly general, they were useful for examining the data states for different categories of data.

Ground Rule 5:

Assign quantitative values to the state subclasses. If sufficient information is not available to allow such assignments, at least the parameters should be assigned. The specific value can then be assigned at a later date. It is important to note that quantitative values should not be assigned unless they are acceptable to the customer. By the same token, the customer should be made aware of the consequences of not having these values assigned. The time, quantity, and quality parameters identified in chapter II represent an implementation of this ground rule.

Define the Constraints for the Supersystem

Ground Rule 6:

Define limits on means preestablished for the supersystem as well as the major components for the supersystem. Essentially, these constraints should identify the basic systems comprising the supersystem. The constraints are usually expressed in mission or planning documents, or, are generally accepted by the customer organization. In the latter case, it is important to differentiate true constraints from assumed constraints which are not necessarily binding. The only way we know to effectively differentiate true constraints from assumed ones is to ask the question "What are the consequences of violating the constraint?" If the answer is "rejection of the concept" or "significant delay or increase of cost," it is generally safe to accept the constraint. This is a judgment the analyst has to make and the nature of constraints makes the judgment a difficult one to make.

As indicated previously, constraints tend to simplify the design process since they reduce the number of alternatives which must be considered. During the early portion of system design, the number of alternatives is so large that the analyst can very easily begin to perseverate. Inadvertently, he will frequently start to accept constraints without question, or even start to assume constraints to help identify avenues of approach. To our knowledge, the only real way to prevent this is to constantly query the validity of each constraint, without necessarily fighting the windmill.

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The constraints described in chapter II indicate that the constraints for the current project were not extensive. However, the time constraints of the project required us to assume certain means constraints. These assumed constraints are described in the assumption section of Chapter II (in the discussion of RCS qualitative requirements). In addition to constraints, it was necessary to continually delimit the scope of the RCS to prevent unnecessary overlap with the SFOF (an adjacent system) and assure proper scope for the RCS, so that exorbitant time was not spent in analyzing an area questionable with respect to whether it should belong in the RCS. Most of these areas are current functions at the SFOF and apparently are performing with considerable success.

Define the Object, Reference, and Adjacent Systems and Their Relationships

Ground Rule 7:

Define the states separating the systems, using the ground rules for establishing the boundaries for the supersystem. The preceding ground rules will usually help identify the systems. The effort in this step should be concentrated on defining the relationships between the systems. At the outset, only the class of states needs to be defined. Later, it may be necessary to define the subclasses, depending on the extent to which the reference system is to be constrained by the adjacent systems. The states between the object system and the reference system will be further defined when the object system is analyzed. Figure 2-3 defines all the major systems in the supersystem for this study.

Define the Set of Object Systems

Ground Rule 8:

Identify the total set of object systems which the reference system must support. Both the states and the relationship between systems should be reexamined to determine whether any given object system alters the requirements (output state) or the relationship between the systems. Where possible, design characteristics of the object system should be obtained. These may be in the form of block schematics and/or performance specifications. Figure 2-2 represents an application of this ground rule.

Considerable difficulty was encountered in this study in attempting to comprise an inclusive list of candidate objective systems. The systems were easily identified at the very general level (e.g., SURVEYOR, ORBITER, MARINER, etc.). The specific configuration was almost impossible to define since many critical design decisions have not yet been made for most of the candidate systems. Thus, it was decided to use a generic spacecraft system with combinations of capabilities from all the candidate systems.

Define the Interface Between the Object and Reference Systems

Ground Rule 9:

Analyze the state changes required of the object system. As indicated previously, the requirement for the reference system is to help the object system go through a series of state changes to meet its objectives. Thus, the specific interfaces between the two systems can be identified. The interfaces in the form of states flowing from the reference system to the object system can then be treated as the requirement for the reference system (see the functions analysis section). The functional-flow logic diagrams (FFLDs) of figures 2-5 through 2-12 represent an application of this ground rule. Tables 2-4 through 2-9 are expansions of the state-change requirements and describe some of the performances required within the functions of the object system. Table 2-10 presents a summary version of the functional requirements of the object system.

Synthesize the Reference System Requirements

This step is primarily one of grouping all the inputs required by the object system which are to be provided by the reference system. Techniques for grouping or synthesizing are discussed in a later portion of this chapter.

The command/control requirements presented in tables 2-11 through 2-17 represent one form of synthesis. This synthesis may appear somewhat strange in that it represents no reduction of data from the primary source, i.e., the spacecraft functional requirements in tables 2-4 through 2-9. Although desirable, synthesis does not necessarily result in a lesser quantity of data. The important factor is information. In this case, much of the data in tables 2-4 through 2-9 had to be retained. However, the differences resulted from synthesizing requirements information presented at higher levels of indentures. The differences exist primarily in columns 4, 5, and 6.

DESIGN CONCEPTUALIZATION

This is probably the most creative aspect of the total design process. Analysis and synthesis may be regarded as processes supporting design conceptualization. Synthesis, after this process, provides a way of checking the adequacy of the design as conceived. Analysis and synthesis before the process (at any given level in the pyramid) provide a way of partitioning and regrouping the system into manageable entities.

Define the Applicable Constraints

Ground Rule 10:

Interrogate the constraints established by the customer. The most important aspect of this step is to accept only those constraints which are necessary and justifiable. One source of constraints is the customer. If the constraint cannot be justified at the given level of conceptualization, the customer is frequently willing to relax the constraint.

Constraints can be justified on the basis of (1) decisions at higher levels in the pyramid, (2) impact by or on adjacent systems (including society), and (3) effect on time and/or cost.

No specific constraint was established for this study. However, the limited time and manpower available for the study required that we assume certain constraints. The constraints were selected primarily to focus attention on what appeared to be the major functions of the RCS. These constraints are expressed in the form of assumptions.

Identify Relevant Design Principles

This is not a simple step in a time-constrained project since design principles are not that plentiful. Principles should be based on sound research data, and many of the data currently available are not sufficiently basic to allow inferences to new situations. Many are restricted to the type of equipment conceived by the experimenter.

If possible, design principles should be developed for the critical performances in the system. Assuming that design principles are not available at the outset, it will be necessary to synthesize available research data. If the critical performances are known at the outset, the development of the principles can be tailored to the need.

Our attempt to develop useful design principles for this study was unsuccessful. Hopefully, JPL can learn from this failure. The failure is probably due to three major factors. First, there was a scarcity of sound research data which related somewhat directly to the design problems anticipated. Second, sufficient man-hours were not planned for this activity. It is very likely that reasonable principles could have been developed if sufficient time had been available to consider more remotely related research. Finally, the activity was initiated concurrently with the requirements analysis (due to schedule constraints) and thus had to be guided by anticipated problems, not the problems identified through requirements analysis.

Our failure to develop principles for this study does not mean that the step should be omitted for we have had considerable success with this step in other studies. Therefore, it is anticipated that the cost effectiveness of the step depends on the validity of the anticipated problems used to guide the search, the relevancy of available data, available man-hours, and the qualifications of available personnel.

Identify Classes of Means and Respective Roles

This step applies only at higher levels in the pyramid. It should be conducted very carefully since it can overly constrain subsequent design activities if a design concept is established prematurely. Theoretically, it should be possible to identify the relevant classes of means if the requirements have been clearly delineated during the previous activities and there are sufficient data on available means. In real life, the requirements are definitized in a series of iterative steps, and it is almost impossible to keep track of all available means.

The schedule and cost constraints for most systems require that a significant portion of the system be comprised of new combinations of existing means. The need for advancement is frequently identified at more specific levels of design. Furthermore, new components are frequently developed at the more specific levels of design.

The type of creativity required at the higher level in the pyramid indicates that the classes of means identified should be those which can be combined to form the system means. All feasible candidates should be identified, along with the characteristics of the class. Each class can then be assigned basic roles in the system for which it is best suited, e.g., detection, primary monitoring, decision making, and calculations. Each class should also be described in terms of factors to which it is sensitive, e.g., environmental conditions, load per unit of time, etc. These factors can then be considered in subsequent analyses. Tables 3-1 through 3-7 represent an application of this ground rule.

FUNCTIONS ANALYSIS

Functions analysis, as viewed by Serendipity Associates, is considerably different from the commonly accepted concept of functions analysis. This is not to imply that our approach is better; however, we have found our approach to be more effective in the types of system with which we have been concerned. The effectiveness of this approach can be lost, however, if the key concepts are violated.

The key concepts of the functions analysis approach are the concepts of state change and analysis. These concepts were described earlier and will not be repeated here. It is important to remember that a function is identified as a result of identifying two adjacent states. The output state is the requirement and the input state is the prerequisite. The performance required of the function is to change the input state to the output state. Most important, it is not enough merely to show the linkages between the functions. In fact, attempting to show just the linkages frequently results in the analysis being means-(functional) oriented, since this can result in the functions being accepted without question.

In the normally accepted functions-analysis approach, the analysis technique is a diagrammatic one. Functions are identified as blocks with assigned nomenclature. The relationships are shown by lines between blocks. This means that the functions are accepted from the outset and are arranged on the diagram. Logic diagrams are now being used to indicate more clearly the complex relationship between functions.

The diagramming technique and logic symbols are used in applying the state-change concept. However, the two approaches differ considerably. Functions are not accepted per se in the state-change concept even in those cases where an extant system is partitioned. Means will be accepted in the case of an extant system, but the functions delineated by applying the state-change concept frequently differ from the functions used in the usual approach.

The technique differs somewhat, depending on whether the system under analysis is extant or a new one under development. Thus, two descriptions are provided: one for the object system and one for the reference system.

Functions Analysis of an Object System

1. Level of Analysis

Ground Rule 11:

Take the analysis to the level where the various types of interfaces with the reference system can be clearly identified. It is difficult to preestablish specifically the level to which the analysis of the object system should be taken. This is an omnilevel rule but it can be used to develop specific rules for a given project. Generally, the level will be dictated by the available time. In the current project, the criteria used were (1) the level commensurate with information available on systems subsequent to SURVEYOR, (2) the level where the relationship between the support functions and data-collection functions was established, and (3) the level where the data-collection functions were examined for each relevant data subclass. Subsequent analyses indicated that meeting the third criterion did not contribute as much to defining the RCS requirements as we had originally anticipated. However, the analysis provided a reason for examining various classes of data-collection mechanisms which was quite fruitful for defining the support requirements in greater detail.

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2. Diagramming

Functional-flow-logic diagrams should be developed at increasing levels of specificity. Between each level, however, ground rules (design concept) should be established to structure the next lower level. Each level of diagram establishes a level of partitioning.

a. Supersystem boundaries

It is not necessary for the supersystem boundaries to be presented in diagram form. However, the class of states and the major subclasses must be defined. Frequently, this will require utilization of other techniques more adaptable to identifying general classes of states, e.g., matrix of planet states by data types. Figure 2-1 and table 2-2 were used in this study.

b. Supersystem components

In the current project, the supersystem components and their basic relationships were established as constraints. Furthermore, they appear to be justifiable constraints. Thus, developing this diagram was simply a matter of properly arranging the components and defining the states linking the components. Only the class of states (e.g., command, scientific data) need to be identified since the primary purpose of the diagram is to see whether adjacent systems need to be analyzed (see figure 2-2).

c. Object system boundaries—Top level

This diagram should represent an expansion of the state expressions of the object system portion of the supersystem components diagram. This will not be a simple task. The diagram per se will not be useful in expanding the state expressions. It will serve simply as a means of documenting the results and providing the boundaries for the next level of analysis.

It is important that the input state of the object system be clearly established since this state will be used in the first step of delineating intermediate state changes, i.e., identifying functions.

The top-level diagram for the object system was omitted in this study since (1) the supersystem diagram identifying the components (figure 2-2) served to bound the object system sufficiently, and (2) only one function of the object system was selected for further analysis.

d. Identify functions

It is important to remember that the functions are to be identified by defining intermediate changes of state. Thus, the ground rules are designed to facilitate the identification of intermediate states.

Ground Rule 12:

Do not assign a nomenclature to any function identified in the process until all necessary intermediate states have been identified. This rule is designed to overcome a general tendency to assign preconceived functions first and then assign states generally associated with that function. There is also a tendency to express the state in terms of "function completed," e.g., the function may be identified as "calibrate" and the state identified as "calibrate completed." This approach results basically in a configuration of preconceived functions.

Ground Rule 13:

Express the state in the present tense. This rule is also one to help prevent the analyst from falling into the trap of accepting preconceived functions without question.

Ground Rule 14:

Determine whether the process of reaching the output state can be initiated and completed with the given input state. The process required to provide the output state may be regarded as the lead function. The nature of the lead function is generally determined by a class in which the output state is a member, e.g., data. Frequently this will require the analyst to make some assumptions about the basic design of the object system. For example, in the current project it was assumed that the sensors would be in a stowed state at touchdown and that all data could not be collected with the sensors in that state. It was also assumed that some sensors would require a controlled environment, would have to change position and location states to acquire the necessary samples, and would require different telemetry modes depending on the signal characteristics. The input state subclasses shown on figure 2-5 were based on these assumptions. In other words, certain assumptions were made about the object to identify subclasses of states which would have to change within the system. Change of state for any subclass would then serve to bound object system functions of specific concern to the reference system.

Ground Rule 15:

If the process cannot be initiated with the specified input state, take each subclass of the input state and identify the specific state required to initiate the process. If the input state for the lead function differs from the input state to the system, place a block between the two states. If the two input states are the same, omit the block and draw a line from the system input state and the lead-function input state.

The position, location, and environment control functions as well as the first transfer-information function in figure 2-5 were not identified when this rule was applied since the input state was sufficient to initiate the data-collection function. These functions were identified when ground rule 17 was applied.

Ground Rule 16:

Determine if a major state change in series (multiplicative) is required within the lead functions. "Major" may be defined as a change in one or more of the parameters relevant to all input state subclasses. Implementing this ground rule requires considerable judgment on the part of the analyst. Only two functions were identified in applying this ground rule to function 1.3. One major change of state was to change the location of data from the spacecraft to the RCS (or SFOF). The second change of state of concern was to change from planet states to data states.

Ground Rule 17:

Identify feasible NOT (adverse) states [1] based on the known characteristics of the classes of means assigned to the lead function and the output states required. The NOT states can be identified by first examining the outputs to determine whether there are general classes of states which would prevent the specified output states. All the states leading from the data-collection function to the support functions in figure 2-5 were identified by applying this ground rule. Functions identified in this manner should be queried further to determine whether additional inputs are required. If so, the basic input state should be examined to determine whether they are sufficient. If not, additional functions should be identified by applying ground rules 15 and 16.

Ground Rule 18:

Inputs required to initiate the function should be assigned 1, and inputs required to complete the function should be assigned 2. If some of the states are required to initiate the function, while others are required to complete the function, the states should be numbered.

3. Documentation

The diagrams serve as one form of documentation (see FFLDs in figures 2-5 through 2-12). It is frequently useful to describe each function separately (see tables 2-4 through 2-9). If such a description is to be provided, it should be oriented towards the performances required within the function, factors affecting such performance, and more specific description of the physical means. The purpose of such documentation is either to guide the analysis at the next lower level or the analysis of the reference system.

Functions Analysis of the Reference System

1. Level of Analysis

Ground Rule 19:

Partition the reference system to the level necessary to clearly identify physical means to implement each function. The term "clearly" can be defined operationally as (1) specifying existing means (or combinations of existing means), or (2) specifying that existing means will not meet the requirements and the required performances are expressed in quantitative terms.

The preceding ground rule indicates that a decision to stop the analysis process can be made only after the subsequent design conceptualization process

[1] In this definition NOT or adverse states consist of both desired but not yet performed states, and contingencies or undesired states.

has been attempted. If sufficient information is not available to arrive at a means decision, the analysis will have to be carried to a more specific level. This usually means that some functions will have to be analyzed to greater depths than others. Generally, proper partitioning at the higher levels will enable the detailed partitioning to be limited to a small number of functions.

It should be noted that each level of analysis will be conducted within the confines established by the means decisions made at the next higher level of design conceptualization. Thus, if a decision is made to allocate all computation processes to a computer, the analysis will be limited to those factors relevant to computer programming and/or design. The analysis will be stopped if the specific computer to be used can be identified and sufficient information is available to allow identification of the type of program to use. Additional (and more specific) information will undoubtedly be required to develop a program. Functions analysis will not include the process required to develop the specific information for programming since this is specific to a given means and is considered to be part of detailed design.

Although two levels of analysis of the RCS were conducted for this study, they should be treated as only one level since no means decision was made in the interim. The analysis was conducted at two levels solely to allow more detailed analysis for some of the functions. This frequently occurs in a time-constrained situation. In fact, this is probably a cost-effective approach since the level of analysis is adjusted to the need for analytical data. The next level of analysis will begin only after the initial physical design concept has been accepted.

2. Diagramming

Development of functional-flow logic diagrams for the reference system will be similar to the process described for the object system. However, there are certain critical differences of which the analyst should be aware. The ground rules will be oriented primarily toward the areas in which differences exist.

The first three steps indicated for the object system (identifying supersystem boundaries, supersystem components, and object system boundaries) need not be repeated for the reference system. It may be necessary, however, to redefine the boundaries for the reference system. Normally this will not be necessary since the boundaries will be established when the boundaries for the object system are established.

In many cases it will be necessary to regroup the state definitions which describe the linkage between the object and reference systems. This is part of the synthesizing task and will not be discussed here. Assuming an adequate synthesis of the reference-system requirements, the diagramming can then be started on each set of reference system output states.

a. Identify functions

This step will be initiated only after a justifiable design concept has been established.

All the ground rules for the object system also apply to the functions analysis of the reference system, except rule number 17. This rule requires identification of the NOT states by considering known characteristics of classes of means. This is not feasible when a nonexisting system is under analysis since the classes of means have not been assigned yet.

This ground rule (when used for the reference system) should be changed to read: <u>Identify feasible NOT states based on the reverse of each subset of the required state and whether additional inputs are required to change the NOT state to the required state.</u> Additional inputs are those required other than the input state(s) of the function within which the NOT state arises. A potential NOT state which does not require an additional input state should not be considered as a NOT state since it should be "handled" within the function.

b. Synthesis

As indicated in the definitions provided earlier in this chapter, synthesis is the process of combining performance entities within a system to form a set. This can be accomplished in either a static or a dynamic manner. A dynamic synthesis is a process wherein the interactions between the functions and resources (means) are taken into account. A static synthesis is one where the system is treated in somewhat of a single-thread manner; i.e., interactions between functions are not considered. In both cases, the objective is to provide a total picture, in quantitative terms, such as measures of system effectiveness. Naturally, the dynamic synthesis is a more phenomenally equivalent representation of the real system and should permit better insight into the RCS.

The reasons for providing the total picture are to (1) check the means decisions made to date and (2) allow the designer to develop or create a means concept. Static synthesis techniques facilitate the latter, whereas the dynamic synthesis techniques facilitate the former.

Static: —The system is usually a complex entity and no one view will necessarily give the total picture. The goal for static synthesis should be to provide as large a grouping of system elements as possible. Since the system is comprised of a hierarchy of both functional and physical means, some hierarchy of synthesis will probably be required. It is not necessary to use only one synthesis form. However, using many different synthesis forms will force the synthesis of the different forms in order to obtain an integrated picture.

The results of synthesis should provide a ready identification of both common and unique factors in the system. Generally, matrices and charts have been quite useful for arranging the relevant data so that common and unique factors can be readily identified. In most cases, the most applicable form can be discussed only after the analyst tries viewing the system from many different directions. His biggest problem will be in trying to identify the factors for which commonality or uniqueness should be sought.

Ground Rule 20:

Identify the factors which are anticipated to affect performance of means decisions. These factors should then be used as the basis for at least one form of synthesis.

Once the functions analysis is initiated, the most singularly useful static synthesis is to summarize all the results of the lower-level analysis at some higher level of function and there to seek commonalities between functions. This is in reverse order to the partitioning and should provide an easy way of relating between functions. This approach will allow both the requirements and the functional means to be viewed together. The items synthesized in this manner should include, but not be limited to, lower-level functions, factors affecting performance, system-/function-effectiveness criteria, and relevant characteristics of the input conditions.

In the current project, a great deal of the static synthesis was accomplished by examining and reexamining the analysis data. Additional documentation was not required in most cases, since only a small number of individuals was involved in the synthesis. Part of the synthesis was accomplished by testing concepts against the requirements indicated in the form of FFLDs and function tables. This facilitated the synthesis as each means concept was applied to a large number of functions to see if the concept was generally valid.

The basic products of synthesis in this project are the command/control requirements presented in tables 2-4 through 2-9, the RCS function descriptions presented subsequent to the RCS function tables, and the various matrices presented in chapter III. Each synthesis product served to initiate the next step in the development process. The command/control requirements signaled the completion of analysis of the object system and initiated analysis of the reference system. The RCS function descriptions signaled the completion of RCS analysis and start of design conceptualization. The matrices in chapter III were developed because the RCS function descriptions did not provide adequate information. In other words, more relevant information had to be synthesized from the existing analytical data.

Dynamic:—A dynamic synthesis of most systems generally requires a model of some s sort. This is a complex process and cannot be adequately covered in this report. Only a summary description is presented here. The technique is primarily one of representing the system functionally in a computer and allowing the computer to simulate the functions in somewhat the same time relationship as they would occur in the real system. This allows the analyst to try out various changes within the system to determine the effect on system effectiveness before committing the change to design. It is obvious that this type of synthesis requires that the functions of the system be defined at a particular level. Static synthesis will be required prior to and after dynamic synthesis.

It has been recognized in recent years that there is a need to determine the relationship between elements of the system and the system objectives. This recognition has resulted in the acceptance of the system-effectiveness concept. System effectiveness is a measure of the extent to which system objectives are (or are predicted to be) met. There are many factors which determine the extent to which the objectives can be met. Moreover, these factors tend to interact and the relationships are seldom linear. This is especially true when resources are shared by many functions and environmental factors have differential factors on different functions.

It is generally agreed that a simulation model is required to obtain some resemblance of precision in measuring system effectiveness for a complex system. All are not agreed on the nature of the simulation model. We have generally found that a model simulating system functions is quite representative of actual system performance. Furthermore, such a model provides highly useful results to the designers since it allows the designer to determine relationships for the specific function or design group with which he is concerned. It also forces his attention on other system variables which interact with the function(s) of concern to him.

The model must be phenomenally equivalent[2] to the real system. In order to achieve adequate equivalence, it is necessary to identify all factors which affect performance and the manner in which the factors affect the performance. This is the same information the designer should normally consider in developing design concepts. However, we have frequently found that in attempting to express the relationship logically or mathematically, it forces more attention to these factors than is normally given, especially with respect to the manner in which relevant performances are or could be affected. Thus, the modeling process itself frequently provides a form of synthesis.

The model provides a systematic means of trying different design or operational concepts at varying levels of detail. Concepts can be evaluated on the basis of the extent to which they differ in contributing to system performance. By using proper experimental design techniques, the model provides a relatively inexpensive way for determining the extent to which one portion of the system contributes to the total system performance.

Certain types of models will allow man to "perform" along with the model, with the model simulating all non-man functions and responding to man's behavior.

Tools—such as the model—for providing quantitative measures of relationships and system effectiveness are useful not only to aid in the development of design concepts, but also to assess the adequacy of the concepts. The original plan for this study was to use the model to assess the concept. However, recent experiences in this and other studies indicate that a more useful approach is to use the model to help establish quantitative requirements and relationships prior to developing a conceptual design. Subsequently the model can be used to test the concept.

[2] i.e., it must possess characteristics equivalent to the system being studied.

Without the quantitative requirements, the designer is forced to rely on judgments. Frequently, the judgments result in means constraints which are difficult to change later on. More important, the designer has no reference whereby to judge the relative merits of different design approaches.

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